W.E.S.C. E/5A/CON/1632/172/099
ENERGY ANALYSIS OF
WAVE ENERGY CONCEPTS
FINAL REPORT SECTION 3
G. JENKINS & R. HARRISON
DECEMBER 1981

SECTION 3

APPENDICES B to E

W.E.S.C. CONTRACT NO. E/5A/CON/1632/172/099

ENERGY ANALYSIS OF WAVE ENERGY CONCEPTS

FINAL REPORT

by

R. HARRISON
and
G. JENKINS

Energy Workshop,
Dept. Physical Sciences,
Sunderland Polytechnic,
Langham Tower,
Ryhope Road,
SUNDERLAND.
SR2 7EE

DECEMBER, 1981

ENERGY WORKSHOP REPORT NO. 24

FINAL REPORT APPENDIX B

W.E.S.C. CONTRACT NO. E/5A/CON/1632/172/099

THE ENERGY REQUIREMENT OF CEMENT FOR USE IN THE CONSTRUCTION OF WAVE ENERGY DEVICES

MAY 1981

G. JENKINS

ENERGY WORKSHOP

SUNDERLAND POLYTECHNIC

Sunderland Polytechnic

1. SUMMARY

* The gross energy requirement of (GER) cements for use in wave energy device construction has been determined and is shown in the Summary, Table 18,

* Cement contributes 83-98% of the energy input to strong concrete (Grade 40). The remainder is contributed by the aggregate, and the energy requirement of this is highly site - specific.

* The relative contribution made by cement to the energy input of wave energy device systems is as follows:

NEL Oscillating Water Column (Breakwater 1980):	18%
Lancaster Flexible Bag (Top Duct 1979/80):	9%
Bristol Oscillating Cylinder (1979/80):	2%

* Large reductions in the gross energy requirements of cements supplied to wave energy device construction sites are possible.

* These reductions fall in three main categories:

  - the use of blended cements (especially Portland Blast-furnace cement)
  - the use of ordinary Portland Cement (OPC) from dry process plants only
  - the use of energy efficient technology to reduce process (direct) energy consumption in ordinary Portland cement works.

* Taking the current Scottish mix of cement supply as the baseline, the possible reductions in gross energy requirement to cements at wave energy device construction sites, by taking the above techniques singly, as follows:

- use of Portland Blast-furnace Cements (from Scottish mix of OPC):	34% reduction
- use of dry process works Ordinary Portland cement (Dunbar):	17% reduction
- use of all process energy savings on current Scottish mix OPC:	16% reduction

* There are many possible combinations of cement supply to wave energy sites. However, the most likely possible reductions in gross energy requirements (GER) are:

- all dry process (Dunbar) OP cement with all process energy savings:	30% reduction
- Portland Blast-furnace Cement made with clinker supplied from dry process (Dunbar) OPC works incorporating all the process energy savings:	50% reduction

* The use of a dedicated plant producing cement in close proximity to the wave energy device construction site was postulated. However there are many uncertainties:

  - the availability of raw materials in suitable combinations
  - the current overcapacity in the cement industry
  - the minimum economic size for a cement plant
  - the annual demand for cement to construct wave energy devices and the length of time for which this demand can be sustained
  - the reduction in demand for OPC from this plant if Portland Blast-furnace Cement is found to be acceptable to device designers

* The reduction in gross energy requirement for cements from such a postulated dedicated plant would be relatively small if all the process energy saving techniques could also be applied to plant at Dunbar cement works. In this case the only savings would be in transport energy, giving reductions in GER of about 7%

* Weighing all the above factors, a dedicated cement works near wave energy device construction sites seems unlikely to be built.

2. Introduction

Most wave energy devices currently under consideration will employ large volumes of concrete in the construction of their main structures. Concrete is made up from three basic constituents; cement; aggregate and water. Of these the major energy input to concrete is embodied in the cement. For a typical strong concrete (Grade 40: $40N/mm^2$ 28 day strength) made at a wave energy device construction site using ordinary portland cement (OPC), from Scottish mix of supply between 83% and 98% of the energy input is embodied in the cement. The precise energy requirement of concrete is highly site specific. The type of aggregate, its availability and proximity to the wave energy device construction site (WEDCS) all affect the energy requirement of the aggregates and therefore of the concrete.

Thus, to study ways of reducing the energy requirement of concrete, it is appropriate to investigate what energy savings are possible in the production of cement for the construction of wave energy devices.

This report concentrates on the current practice in the U.K. cement industry and then outlines how the energy saving options described in Energy Audit 11 'The Cement Industry' (1) can be applied to the production of cement which will then be supplied, to wave energy device construction sites in Scotland.

The contribution that the device structures make to the energy input to the whole wave energy system varies with the system studied. Thus the proportion of the total system energy input which is embodied in the cement used to construct the devices varies widely between wave energy systems. For example, for the NEL Oscillating Water Column Breakwater device, the cement makes up 18% of the total energy input to the system, which makes it one of the largest single energy inputs. For this device then, any reduction made in the energy requirement will have an important bearing on its viability in energy terms.

In other wave energy devices cement plays a less important role. The Lancaster Flexible Bag system has about 9% of its energy input embodied in the cement (2), whereas the Bristol Oscillating Cylinder device has only 2%. The latter device has its major energy inputs in the power take off machinery and mooring areas.

3. Current Cement Making Practice

Ordinary Portland Cement is made by two distinct processes in the U.K., the Wet Process, and the Dry Process. Production of 16.1 million tonnes of cement in 1979 was in the proportion of 69% by the wet process and 31% by the dry process, (1). The details of the cement making process vary widely. No two works are the same and there may well be differences within a single works as new kilns and equipment are added. For example, the wet and dry processes may operate side by side using the same raw materials and producing the same end product (1). The two processes differ in the way materials are dealt with up to the calcining stage.

3.1 Wet Process

In the wet process the raw materials are reduced to the required fineness in water and are blended, stored and fed into the kiln as a fluid slurry. Much of the kiln firing energy is used to evaporate the water which is typically 30-40% by weight in this process. Technically the wet process is favoured in areas which have 'wet' raw material such as chalk and clay. The process energy requirement of cement manufactured by this method is given in column 'A' of Table 1.

3.2 Dry Process

In this process, the raw materials, usually limestone and shale are ground to a 'meal', during which the moisture content is reduced. It is blended and normally passed through a preheater system which completes the drying.

The preheater stage utilizes the heat remaining in the exhaust gases after they have passed through the kiln itself.

Process energy requirement (PER) is the direct energy used in processing the raw materials to manufacture cement expressed in terms of primary energy (GJ_t) (3).

The process energy requirement for the production of OPC by this method is given in column B of Table 1.

Semi-wet and semi-dry processes are also in use where the raw feed is prepared by the wet or dry process depending on raw materials and made into pellets of medium moisture content then fed to a grate preheater before calcining.

3.3 U.K. Average Mix of Cement Production (1976)

The process energy requirement of U.K. average mix cement is shown in column C of Table 1, based on the proportions of wet/dry process plants of 69/31.

TABLE 1 PROCESS ENERGY USED IN ORDINARY PORTLAND CEMENT MANUFACTURE (1976) (FROM REF. 1)

	Process Stage	Fuel GJ/tonne (heat supplied)			Electrical Power kWh/tonne (heat supplied)			Fuel Factor	Primary Energy GJ_t/tonne		
		Wet	Dry	UK AV[2]	Wet	Dry	UK AV		A Wet	B Dry	C UK AV
1	Raw Material winning	-	-	-	3	3	3	3.30	0.04	0.04	0.04
2	Feed Processing	-	-	-	15	40	23	3.30	0.18	0.48	0.27
3	Kiln Burning Fuel supplied	6.1	-	-	-	-	-	1.06[1]	6.47	-	-
		-	3.3	-	-	-	-	1.07[1]	-	3.55	-
		-	-	5.3	-	-	-	1.05[1]	-	-	5.57
4	Kiln Burning Electric Power	-	-	-	30	30	30	3.30	0.36	0.36	0.36
5	Cement Processing	-	-	-	45	45	45	3.30	0.53	0.53	0.53
	Total	-	-	-							
	Process Energy Requirement	-	-	-	-	-	-	-	7.58	4.96	6.77

Fuel factor: $\frac{\text{primary energy } (GJ_t)}{\text{heat supplied } (GJ)}$

1 derived from mix of fuels used in the process

2 U.K. average process mix 69% wet process/31% dry process

4. Gross energy requirement of Ordinary Portland Cement: Current U.K. Practice

The gross energy requirement (GER)* covers all of the energy embodied in a unit of the final product. It includes the main process energy requirement (PER) plus the indirect energy used to furnish the capital equipment necessary in production, plus the energy used directly and indirectly in transporting the product to the point of use (3).

Energy Audit 11 'The Cement Industry' (1) gives values for the process energy requirements only, and these have been converted to gigajoules (primary energy) per tonne in Table 1, using the multiplication factors given in Reference (1) to convert from purchased fuel to primary energy. The indirect energy used for the provision of capital plant etc., is determined in this case, based on data from the 1968 Census of Production (4) which is, at present, the only data available applicable to the U.K. This indirect energy added 6% to the direct energy used by the Cement Industry in 1968.

The energy used to transport the cement to the final user has been included assuming a typical 100 km delivery distance, 70 km by rail and 30 km by road (5). This will obviously vary with the site hence for wave energy device construction sites, more specific assumptions have been made. (See Section 5). The typical gross energy requirements of Ordinary Portland Cement produced by the wet process, dry process and the U.K. average mix are shown in Table 2.

Ordinary Portland Cement

Typical construction site: England

Wet Process OPC GER = 8.17 GJ_t/tonne
Dry Process OPC GER = 5.40 GJ_t/tonne
U.K. Average Mix OPC GER = 7.32 GJ_t/tonne

* GER = PER + Capital Energy + Transport Energy

TABLE 2 GROSS ENERGY REQUIREMENT OF CEMENT: CURRENT U.K. PRACTICE (1976)

	Energy Requirement GJ_t/tonne			
	Wet Process	Dry Process	Average (1976 Mix)	Notes
Direct Energy	7.58	4.96	6.77	Table 1
Indirect Energy (Capital Eqpt etc)	0.45	0.30	0.41	6% of direct in 1968 (4)
Sub Total (excluding Transport Energy)	8.03	5.26	7.18	
Mixed Transport Energy (70 km Rail/30 km Road)	0.14	0.14	0.14	Road 1.87 (5) MJ/t Km Rail 1.16 MJ/t Km
Typical Energy Requirement	8.17	5.40	7.32	

5. Gross Energy Requirement of Ordinary Portland Cement for Wave Energy Devices

5.1 Location of Wave Energy Device Construction Sites

The major difference between the gross energy requirement of ordinary Portland cement used in general construction and that of cement for use in wave energy device construction is in the extra transport energy required. This is due to the large distances between current cement works and the North Sea Oil construction yards envisaged as wave energy device production facilities. A list of likely sites and their distance from the cement grinding plant at Gartsherrie, Strathclyde (see Section 6) which is 13 km from Glasgow, and Dunbar cement (see Section 5.2) works is given in Table 3.

An average of these distances is used in further work because the scale of wave energy devices means that several sites may be necessary for a realistic construction scheme (6).

5.2 Average Scottish Mix of Supply for O.P.C.

The mix of supply of ordinary Portland cement in Scotland has been estimated by Smith (7) to be 57% from Dunbar works, 19% imported clinker ground to O.P.C. in the Glasgow area, and 24% imported finished cement from England, Northern Ireland and Eire. To simplify the analysis it has been assumed that imported clinker and cement has its source in the English Midlands, and is transported wholly by rail to the Glasgow area. The plant mix used to supply this clinker and cement has been assumed to be the average U.K. mix of production adjusted to allow for the Dunbar works production to be assessed separately (See Section 5.3). This mix has a wet/dry process ratio of 74/26.

The gross energy requirement ordinary Portland cement in the Glasgow area is shown in Table 4.

The gross energy requirement of ordinary Portland cement for wave energy construction sites can be determined by reference to Table 3. Distance direct from Dunbar to the average site is 293 km and from Glasgow (Gartsherrie) to the average site is 197 km. It is assumed that this transport is 70% by rail, 30% by road, using this Scottish average, modal mix of supply, the gross energy requirement of cement to construct wave energy devices is shown in Table 4.

TABLE 3 DISTANCES TO WAVE ENERGY DEVICE CONSTRUCTION SITES FROM SCOTTISH CEMENT PLANTS

	Distance (km)		
	Gartsherrie (Glasgow) to:	Dunbar via Gartsherrie to:	Dunbar Direct to:
Construction Site			
Ardyne Point	145	255	255
Hunterston	72	182	182
Portavadie	145	255	255
Kishorn	320	430	427
Nigg Bay	302	512	344
Average of Five Sites	197	327	293

TABLE 4 GROSS ENERGY REQUIREMENT OF ORDINARY PORTLAND: CEMENT FOR USE IN WAVE ENERGY DEVICE CONSTRUCTION

SCOTTISH MIX OF OPC SUPPLY

	DUNBAR O.P.C.	IMPORTED O.P.C. CLINKER GROUND IN SCOTLAND	IMPORTED O.P.C.	AVERAGE SCOTTISH MIX	NOTES:
Modal Mix	57%	19%	24%	100%	Smith (7)
Direct & Indirect Energy (GJ per tonne)	5.14	7.31 (1)	7.31 (1)	-	(1) U.K. mix with out Dunbar: split wet/dry 74%/26%
Transport Energy to Glasgow (GJ_t per tonne)	0.13 (2)	0.55 (3)	0.55 (3)	-	(2) Dunbar to Glasgow (3) English Midlands to Glasgow by rail @ 1.16 MJ/t km
Gross Energy Requirement Glasgow Area	5.27	7.86	7.86	6.38	GJ_t per tonne
Transport Energy to Site	0.40 (4)	0.27	0.27	-	(4) Dunbar to site direct (MIXED BASIS)
Gross Energy Requirement of O.P.C. Wave Energy Device Construction Site	5.54	8.13	8.13	6.65	GJ_t per tonne

Ordinary Portland Cement, wave energy devices: Scottish Mix

<u>$GER = 6.65\ GJ_t/tonne$</u>

5.3 All OPC Supplied from Dunbar Works

At present the nearest cement works to likely wave energy device construction sites is at Dunbar in Lothian Region. This is also a dry-process works using coal-fired kilns and this neatly encapsulates the major energy saving option available for U.K. cement manufacture, namely the wholesale change from the wet process to the dry process (see Section 8.1)

Production capacity of Dunbar works is 990,000 tonnes 3 coal fired kilns (1).

The assumption has been made that the process fuel usage is similar to that given in Table 4 of Ref (1) for dry process works, bearing in mind that the kilns are coal fired rather than having the U.K. (1977) mix of kiln capacity which was 84% coal fired, 11% gas fired and 5% oil fired (1).

The gross energy requirement for ordinary Portland cement produced at Dunbar and transported the 293 km (average) to wave energy device construction sites is given in Table 5; of this about 7% is transport energy.

Dunbar OPC for wave energy devices:

<u>$GER = 5.54\ GJ_t/tonne$</u>

TABLE 5 ENERGY REQUIREMENT OF CEMENT FOR WAVE ENERGY DEVICES, CURRENT PRACTICE

Cement Source: Dunbar (Dry Process Works, Coal Fired Kilns)

	Energy Requirement GJ_t/tonne	
Direct Energy	4.84*	coal fired plant, assuming plant as in Energy Audit No. 11
Indirect Energy	0.30	6% of above from statistical data (ERG 006)(4)
Transport Energy	0.40	293 km transport (route) Rail 70% @ 1.16 MJ/t km Road 30% @ 1.87 MJ/t km Mixed i.e. @ 1.38 MJ/t km
Gross Energy Requirement	5.54	at average wave energy device construction site

* differs from Table 4, Energy Audit No. 11 Cement Industry, by being coal fired thus primary energy usage different from average mix (84% coal, 11% gas, 5% oil).

6. Dedicated Plant

There have been suggestions that the use of dedicated plants located close to wave energy device construction sites could make considerable cost savings for a large long term power station scheme. Production of material inputs such as cement, reinforcing bar, prestressing wire or, in the case of steel devices, steel plate and sections, have been suggested as major items for which savings could be made by the use of dedicated plants.

6.1 Factors affecting the choice of "dedicated" or existing plant for the production of OPC for wave energy devices

* The expected annual demand for cement for wave energy device construction and the time period during which the demand can be sustained. An illustration of expected annual demand is shown in Table 6 for the most recent wave energy devices. Other estimates for 1978 device resource requirements can be found in 'Appraisial of Mass Production Costs for Wave Energy Devices' PE Consulting Group (8).

* The spare capacity of the existing U.K. cement industry is as follows (1977-78 figures):

Current capacity:	20.1 million tonnes
Current Production:	14.4 million tonnes
Spare capacity:	5.7 million tonnes

Source: Ref. (1)

This spare capacity is approximately eleven times the predicted maximum annual cement demand for wave energy devices, so any wave energy construction scheme will have only a small impact on the cement industry (6), "Any upturn in the market is likely to be small in the forseeable future" (1).

* The use of a dedicated plant may be justified on energy grounds (see Section 6.2) but would be difficult to justify on economic grounds. The extra investment in a medium sized plant (around 600,000 tonnes per annum) at a capital cost of £1000 per annual tonne would need a capital investment of around £60 million, and the plant typically has a lifetime of 30 years (1).

Minimum kiln size is around 500,000 tonnes per year, and there are no significant energy savings with kiln sizes above this (1).

TABLE 6 ANNUAL DEMAND FOR CEMENT FOR WAVE ENERGY DEVICE CONSTRUCTION

Device	Annual Cement Demand tonnes	No. of Devices Per Year	No. of Facilities	Duration of 2GW Scheme Construction	No. of Devices in 2GW Scheme
NEL (Breakwater) 1980	500,000	120 (yrs 2-10)	7 existing (3 at Ardyne Pt)	7 year	782
LFB (Top Duct) 1979	85,000	44	1	10 year	435
Bristol Cylinder (1979)	120,000	100	1	9 year	930

Thus for the less massive devices a dedicated plant looks unlikely. For the NEL Breakwater device it may be a possibility but the device team are contemplating building these devices at existing oil rig yards (Table 3) which are widely spread around Scotland. Bearing in mind that most savings over existing capacity would come from diminished transport costs, there would be little economic justification for a dedicated plant being built to serve these widespread sites.

6.2 Gross Energy Requirement of Ordinary Portland Cement from a Dedicated Plant

To illustrate possible energy savings it has been assumed that a single dedicated cement plant serving one large construction site for building a device with a large concrete input is used. This depends to a large extent on the availability of raw materials for cement production near to the wavepower construction site. If it can be assumed that these are available and that the dedicated cement plant is 10 km from the single, large construction site, then an estimate of the savings in energy for transport can be made. These calculations, have assumed that the works operates on the dry process (similar to Dunbar) coal fired, and the coal is brought from the Scottish Midlands by train, and the production rate is 8 tonnes of cement per tonne of coal (1).

The results of this projection are shown in Table 7 where they are compared with cement supplied from Dunbar. They do not take into account any energy savings from improved processing, which will be dealt with in Section 8.4

It is clear that the energy savings available on transport are small, around 6% of the gross energy requirement of cement from an existing plant at Dunbar, although cost savings may be larger. For example "while distribution accounts for only about 2 per cent of the Cement Industry energy usage on a heat supplied basis, the costs of transportation represent about 13 per cent of the cement price" (1).

Table 7 Energy Requirement of Cement for Wave Energy Devices From a Dedicated Plant: Current Technology

Dedicated Plant: Dry Process
Coal Fired
Current Technology
10 km from Site
Rail Linked

	Energy Requirements GJ_t/tonne		Notes
	Dedicated Plant	Dunbar	
Direct Energy	4.84	4.84	for process improvements see section 7
Indirect Energy	0.30	0.30	
Transport Energy	-	0.40	mixed basis
Coal to Plant	0.027	-	by Rail
Cement to Site	0.010	-	by Rail
TOTAL	5.18	5.54	

7. The Use of Portland Blast Furnace Cement

7.1 Blast Furnace Slag Cements in Britain

It has often been suggested (1, 7, 9) that more extensive use could be made of Portland Blastfurnace Cement. This is a cement which incorporates a substantial proportion, up to 65%, of ground granulated blast furnace slag (10). The blast furnace slag acts as a latent hydraulic binding agent (11) but cannot be used on its own as a cement, it must be intimately mixed with ordinary Portland cement. This can be carried out either in the cement mixer on site by use of a proprietary ground granulated slag. For example the latter is sold under the trade name 'Cemsave' by the Frodingham Cement Co. Ltd, Scunthorpe (7). It can also be manufactured by grinding together OPC Clinker and granulated blast furnace slag to make Portland Blastfurnace Cement (10). This latter process is carried out by Tunnel Cement Co. at Gartsherrie in Strathclyde (1) and the cement has the proportions of 65% OPC clinker and 35% granulated blast furnace slag. This cement has been manufactured in Scotland for 65 years (12).

7.2 Granulated Blastfurnace Slag

Granulated blast furnace slag is produced close to the blastfurnace by cooling slag with water. Only a small proportion of British blast furnace slag is granulated (approximately 1.3%) (7), the rest being either air cooled and used for roadstone, railway ballast, etc. (95.4%) or it is foamed or expanded in order to produce lightweight aggregate for concrete (3.1%). Blastfurnace slag is an interesting case of a by-product for which markets have been developed over the years, and it is now almost all used (13). Any extra production of granulated blast furnace slag for cement would have to be diverted from production of a lower value product such as roadstone.

Current production of granulated blast furnace slag is about 0.1 million tonnes p.a.. With investment in new granulating plant by British Steel Corporation this could be increased within 10 years to perhaps 10 million tonnes p.a. if increased use could be made of Portland Blastfurnace Cement (1).

7.3 Blastfurnace Slag Cements in Europe

Portland Blastfurnace cement finds only a limited application in the U.K. At present only 0.1% of total cement supplied comes in this category (1). A similar amount of ground granulated blast furnace slag is supplied direct to end users at the construction site (7).

This contrasts sharply with other European countries. For example, in 1974, in the Netherlands 61% of all cement produced was in the form of slag cements (14, 15) in West Germany 23% (14), in Italy 10% (14). [The latter also produces a substantial proportion of pozzolanic cements]. France used 63% of all cement as blended cement (9). Kreijger (15) estimates the energy requirements of 'Hoogovenzement' (containing between 31% and 85% grandulated blastfurnace slag) to be only 2.95 GJ/tonne on a Dutch weighted average of production.

7.4 Properties of Portland Blastfurnace Cement

Portland Blastfurnace cement produced to BS 146 (10) can be used as a direct replacement for Ordinary Portland cement in the design of normal concrete mixes (16). However, it develops strength more slowly and requires more careful handling at extremes of temperature (12, 17). Orchard (18) states "Portland Blastfurnace Cement therefore tends to be weaker at early ages than ordinary Portland cement but at an age of one to two years it may be equally strong or even stronger. It is slightly more resistant to sulphates and peaty or slightly acidic waters than OPC and is often specified for marine work. It behaves in a similar manner, when reinforced, to other cements". The 28 day strength of Portland Blastfurnace Cement concrete is 64% of the 360 day strength, whilst the 28 day strength of OPC is 74% of the 360 day strength (17). This low early strength has the advantage that there is lower heat of hydration, so that thermal stresses are reduced in massive concrete sections by using Portland Blastfurnace Cement. However, there are disadvantages that could be forseen in the use if Portland Blastfurnace cement relating to low temperature concreting, the striking of shuttering and the early use of the concrete for load bearing. The latter may apply to wave energy devices which are slip formed on submersible platforms (e.g. Bristol Oscillating Cylinder) or are slip formed whilst the structure is ballasted down into the sea at an inshore floating berth (e.g. NEL Breakwater Device) (4).

The advantages and disadvantages of Portland Blastfurnace cement for use in wave energy device construction are summarised on Table 8.

TABLE 8 PORTLAND BLASTFURNACE CEMENT FOR USE IN WAVE ENERGY DEVICES

ADVANTAGES

1. Significant energy savings possible.
2. Similar strengths to O.P.C. after 1 year.
3. Better resistance than OPC in marine environment.
4. Low heat of hydration easing design constraints on large sections.
5. Substantial cost savings are possible.

DISADVANTAGES

1. Low early strength could cause problems in slipforming devices which need substantial early strength.
2. Low temperature concreting is more difficult.
3. Increased demand for slag cements may meet resistance from OPC manufacturers in the current depressed market,
4. Increased granulating and grinding plant may be required.

7.5 Gross Energy Requirement of Portland Blast Furnace Cement For Use in Wave Energy Device Construction

The energy requirement for Portland Blastfurnace Cement can be separated into the energy requirements for the production of its component parts in proportion to their respective weights in the final cement. Portland Blastfurnace cement manufactured in the U.K. has the constituency of 65% ordinary Portland Cement and 35% ground granulated blastfurnace slag (1). The energy requirement of ordinary Portland Cement for wave energy device construction has been calculated in Section 5.2

The energy requirement of the granulated blastfurnace slag is determined using the IFIAS energy analysis conventions on the partitioning of products. (3). As the slag is a by-product of pig-iron manufacture, rather than a joint product, all the energy used in mining, preparing and in blastfurnace operations is allocated to the main product i.e. pig-iron. Blast furnace slag, as it leaves the furnace, is allotted zero energy requirement. In the production of ground granulated blastfurnace slag, grinding has an electrical energy requirement of 177 MJ_e/tonne (7) as slag is substantially harder than ordinary Portland cement clinker. Similar figures are given by Kiel (11) for German slags.

The gross energy requirement of producing Portland Blastfurnace Cement to BS146 in the Glasgow area is given in Table 9, using the current Scottish mix of O.P. cement supply. The proportions are 65% OPC, 35% granulated blast furnace slag for this cement. This table also gives the gross energy requirement of this Portland Blastfurnace Cement delivered to a typical wave energy device construction site.

Portland Blastfurnace Cement: Scottish Mix O.P. Cement Supply

G.E.R. (Glasgow Area) = 4.36 GJ_t/tonne

G.E.R. (wave energy construction site) = 4.63 GJ_t/tonne

TABLE 9 GROSS ENERGY REQUIREMENT OF PORTLAND BLASTFURNACE CEMENT: USING CURRENT SCOTTISH MIX OF O.P.C. SUPPLY

OPC Source: Current Scottish Mix
Grinding Plant: Gartsherrie, Strathclyde
Transport to Site: Mixed Basis 70% Rail, 30% Road

	Energy Requirement GJ_t		Notes
	per tonne intermediate	per tonne final product	
Ordinary Portland Cement			65% by weight See Table 4
Direct + Indirect + Transport Energy	6.38	4.15	Includes grinding energy for cement transport to Gartsherrie
Granulated Blast-Furnace Slag			35% by weight
Direct Energy	0.54	0.21	177 MJ_e/tonne Slag grinding energy from Smith (7)
Indirect Energy	0.05		Assumed 10% of above
Gross Energy Requirement Glasgow Area	-	4.36	
Transport to Site	-	0.27	197 km at 70% rail, 30% road
Gross Energy Requirement at Wave Energy Construction Site	-	4.63	

If the Portland Blastfurnace Cement were produced at Gartsherrie using only cement from a dry process works such as Dunbar, the result is a cement with a very low energy requirement. This is shown in Table 10.

Portland Blastfurnace Cement: All OPC from Dunbar

G.E.R. (Glasgow Area) = 3.64 GJ_t/tonne

G.E.R. (wave energy device construction site) = 3.91 GJ_t/tonne

This is an option which could be considered for the production of wave energy devices. At present the Gartsherrie works has an overall grinding capacity of 133,000 tonnes p.a., including around 40,000 tonnes of granulated blastfurnace slag. Thus if, for example the NEL Breakwater Device were to be constructed wholly using Portland Blastfurnace cement, new grinding capacity may have to be built, along with new granulating plant at steelworks.

TABLE 10 GROSS ENERGY REQUIREMENT OF PORTLAND BLASTFURNACE CEMENT: USING DUNBAR AS SOURCE OF O.P.C. SUPPLY

OPC Source: Dunbar
Grinding Plant: Gartsherrie, Strathclyde

-	Energy Requirement GJ_t		Notes
	per tonne intermediate	per tonne final product	
Ordinary Portland Cement: Dunbar (Dry Process)			65% by weight
Direct + Indirect + Transport Energy	5.27	3.43	See Table 4 includes grinding energy for cement
Granulated Blast-furnace Slag: Gartsherrie			35% by weight
Direct + Indirect Energy	0.59	0.21	See Table 8
Gross Energy Requirement			
Glasgow Area	-	3.64	
Transport Energy To Site	-	0.27	Mixed 197 km basis @ 1.38 MJ/km
Gross Energy Requriement at Wave Energy Construction Site	-	3.91	

8. Energy Savings Possible in the Production of Cement for Wave Energy Devices

The reader is advised to refer to the Energy Audit No. 11, Cement Industry (1) for a thorough treatment of possible energy savings in the U.K. cement industry. Many of the energy savings possible have already been outlined in this report:

8.1 Wet to Dry Process Conversion

This offers the largest potential for energy saving in the U.K. and if conversion were made completely to the dry process it is estimated that 1.0 million tonnes of coal equivalent of primary energy could be saved, some 22% of primary energy used by the industry in 1979 (1). This saving is related to the use of cement for wave energy device construction in Section 5.3, Table 5, referring to the Dunbar works, which operates on the dry process, and Section 6.2 relating to a dedicated plant operating using this process.

8.2 Blended Cements

The use of cements blended with ground granulated blast furnace slag, or pulverized fuel ash were studied (1). Widespread use of these cements up to a quarter of current production (4.5 million tonnes) was envisaged. The use of 4.5 million tonnes, 35% blastfurnace slag cement would save an estimated 0.33 mtce (See Section 7).

The use of 4.5 million tonnes of a 20% of a cement would save an estimated 0.15 mtce.

However, the Energy Audit (1) opted for the recommendation to produce more blast furnace slag cement, as it was preferred by both the industry and the Building Research Establishment and was more likely to gain customer acceptance. For these reasons this report concentrates on the blast furnace slag cement option.

8.3 Pulverised Fuel Ash Cement

However, for illustrative purposes, the energy requirement of cement containing 20% pulverised fuel ash as a pozzolan have been tabulated in Tables 11 and 12 for use in wave energy devices. This assumes both that suitable pfa is available from Scottish baseload electricity generating stations, and that this cement will be acceptable for use in the high-strength applications envisaged for wave energy device structures.

Table 11 Gross Energy Requirement of Blended 20% Pulverised Fly Ash Cement for Wave Energy Devices.

OPC Source: Scottish mix of supply

pfa content: 20% by weight

pfa source: Kincardine Power Station

	Energy Requirement GJ_t		Notes
	per tonne intermediate	per tonne final product	
Ordinary Portland Cement Direct + Indirect + Transport	6.38	5.10	inc. transport to Glasgow
Pulverised Fuel Ash Direct + Energy Indirect Energy	0.08 0.01	0.02	50-100 MJ/tonne for grading blending; Gutt (11)
Transport Energy To Site	-	0.27	OPC: Glasgow pfa: Kincardine 70% rail 30% road
Gross Energy Requirement at Wave Energy Construction Site	-	5.39	

Table 12 Gross Energy Requirement of Blended 20%

Pulverised Fly Ash Cement for Wave Energy Devices

OPC Source: Dunbar
pfa content: 20% by weight
pfa source: Kincardine

	Energy Requirement GJ_t		Notes
	per tonne intermediate	per tonne final product	
Ordinary Portland Cement Direct + Indirect + Transport	5.27	4.22	Transport to Glasgow
Pulverised Fuel Ash Direct + Indirect	0.09	0.02	Content 20% by weight Gutt (11)
Transport Energy to Site	-	0.27	OPC from Glasgow pfa from Kincardine
Gross Energy Requirement At Wave Energy Construction Site	-	4.51	

Blended 20% pulverised fuel ash cement

GER (Scottish mix of OPC supply) = 5.39 GJ_t/tonne

GER (all OPC from Dunbar) = 4.51 GJ_t/tonne

8.4 Other Possible Savings

The Energy Audit outlines other possible savings that could be made to existing plant. These are shown in Table 13 along with possible national energy savings and percentages of current energy use. Largest savings come from increased waste heat utilization and development of improved insulating refractories.

If all the process energy savings in Category A can be applied simultaneously, an overall saving of 17.1% could be made. If these techniques can all be applied to, say, a dry process kiln as at Dunbar, an estimate of the likely minimum energy requirement can be made and is shown in the first column of Table 14, assuming this 17.1% improvement can be made at the existing plant. These savings applied to the dedicated plant proposed in Section 6.2 and Table 7 are shown in Table 15. This is likely to be the lowest gross energy requirement possible for ordinary Portland cement for wave energy device construction in the next few years. The use of all of the possible energy savings technologies could be incorporated at the design stage in a dedicated plant. However, it must be remembered that this plant to speculative and depends upon many factors, the chief being the availability of raw materials.

Without the construction of a dedicated plant, ordinary Portland cement must be supplied from existing plants. Dunbar would be the obvious choice, and if all the savings outlined above could be made, and all cement could be supplied from this plant, savings of 30% over the current Scottish mix of OPC supply are possible.

8.5 Maximum Possible Savings

The lowest gross energy requirement of cement supplied for wave energy device construction, possible in the near future is outlined in Table 16. This entails the production of Portland Blastfurnace Cement with O.P. cement supplied from Dunbar and ground with blast-furnace slag at Gartsherrie before being transported to site.

Table 13 Possible Process Energy Savings

For O.P.C. Production

	Technique	Savings Primary Energy m.t.c.e.	Savings % of present consumption
A	All Processes		
1	Waste heat utilisation	0.4	8.9%
2	Insulating refractories development	0.3	6.7%
3	Increased gypsum addition	0.035	0.8%
4	Improved cement grinding	0.02	0.4%
5	Grinding aids for cement	0.015	0.3%
	TOTAL SAVINGS	0.77	17.1%
B	Wet Process Only		
1	Slurry moisture additives development and fixation of alkalis in kiln dust	0.16	3.6%

Source: Reference 1

Table 14 Possible Savings in Energy Requirement of OPC from the Scottish Mix of Supply (with no wet to dry conversion or blended cement use)

(for current values see Table 4)

	Dunbar OPC	Imported OPC Clinker Ground in Scotland	Imported OPC	Scottish Mix of Supply	Notes
Modal Split	57%	19%	24%	100%	
Direct Energy (GJ_t/tonne)	4.01[1]	5.65[2]	5.65[2]	4.72	1 Category A savings only 2 Category A & B savings in proportion to UK mix without Dunbar as Table 4
Indirect Energy (GJ_t/tonne)	0.24	0.34	0.34	0.28	
Transport Energy To Glasgow	0.13	0.55	0.55	0.31	
GER Glasgow Area	4.38	6.54	6.54	5.31	(includes all grinding energy)
Transport Energy to Site	0.40	0.27	0.27		3 Direct as Table 4
GER Wave Energy Device Construction Site	4.65	6.81	6.81	5.58	Assuming all process savings made concurrently

Table 15 Possible Savings in Energy Requirement of Ordinary Portland Cement at a Dedicated Plant

OPC Source: Dedicated Plant
Coal Source: Glasgow Area

	Energy Requirement GJ_t/tonne		Notes
	Current (Table 7)	Possible	
Direct Energy	4.84	4.01	All techniques in category A (17.1% saving) on Table 13
Indirect Energy	0.30	0.24	
Coal Transport Energy	0.03[1]	0.03	at 0.125 tonnes coal per tonne cement, 1) 197 km by rail, 2) 10km by rail
Cement Transport Energy	0.01[2]	0.01	
Gross Energy Requirement at Wave Energy Device Construction Site	5.18	4.28	

Table 16 Possible Maximum Savings Using All Portland Blastfurnace Cement

OPC Source: Dunbar See Table 10

	Energy Requirement GJ_t/tonne Final Product		Notes
	Current (Table 18)	Possible	
Ordinary Portland Cement			
Dunbar			
Direct Energy	3.15	2.61	All Category A savings from Table 13 65% OPC, 35% BF Slag.
Indirect Energy	0.20	0.16	
Transport to Gartsherrie	0.08	0.08	
Blastfurnace Slag			
Gartsherrie			
Direct Energy	0.19	0.188	Slag allocated zero energy requirement Improvement of 1% assumed for grinding teachniques
Indirect Energy	0.02	0.02	
Transport to Site	0.27	0.27	
Gross Energy Requirement for P.B.F.C. At Wave Energy Device Construction Site	3.91	3.33	GJ_t/tonne delivered

These figures assume:

1. Use of Portland Blastfurnace Cement to BS 146 with 35% blastfurnace slag content.

2. All Ordinary Portland Cement clinker for above comes from a coal-fired dry process plant at Dunbar.

3. Dry process plant incorporates the savings outlined in Sections 8.3 to maximum effect (i.e. 17.1% savings).

4. An improvement of 1% is made in the energy requirements for slag grinding.

Possible Savings: Portland Blastfurnace Cement
at Wave Energy Construction Site
(OPC from Dunbar)

Possible GER = 3.33 GJ_t/tonne

Further savings are possible if a dedicated plant was thought to be feasible. However, the use of blastfurnace slag in the blended cement means a reduction in the quantity of ordinary Portland cement needed from the dedicated plant which would in turn affect the economics of the plant. However, the example shown in Table 17 can be used as an illustration of the lowest possible energy requirements for cement supplied to wave energy device construction in the near-to-medium term future.

Maximum Energy Savings Possible

Portland Blastfurnace Cement Using OPC from Dedicated Dry Process Works at Wave Energy Construction Site

Possible GER = 3.08 GJ_t/tonne

Table 17 Maximum Possible Savings using Dedicated Dry Process Plant Producing Portland Blastfurnace Cement

OPC Source: Dedicated Plant 10 km from construction site

Granulated Blastfurnace Slag Source: Glasgow Area

Slag Grinding: Dedicated Plant

Coal Source: Glasgow Area

Transport: Rail

	Energy Requirement GJ_t/tonne final product		Notes
	Current	Possible	
O.P.C.			
Direct Energy	3.15	2.61	65% by weight
Indirect Energy	0.20	0.16	
Coal Transport Energy	0.02	0.02	by rail from Glasgow area
Granulated Blastfurnace Slag			
Direct Energy	0.19	0.19	35% by weight
Indirect Energy	0.02	0.02	
Slag Transport Energy	0.08	0.01	by rail from Glasgow area
P.B.F. Cement Transport Energy	0.01	0.01	by rail 10 km
Gross Energy Requirement for P.B.F.C. at Wave Energy Construction Site	3.62	3.08	GJ_t/tonne delivered

Table 18 Summary: Gross Energy Requirement of Cements

	Cement Type	Source	Use	Current Process	Possible Process	Gross-Energy Requirement GJ_t/tonne	Table
1	O.P.C.	U.K. Average	Typical English construction site	*		7.32	2
2	O.P.C.	Wet Process Plant	"	*		8.17	2
3	O.P.C.	Dry Process Plant	"	*		5.40	2
4	O.P.C.	Scottish Average	Glasgow	*		6.38	4
5	O.P.C.	Dunbar	Glasgow	*		5.27	4
6	O.P.C.	Scottish Average	W.E.D.C.S.	*		6.65	4
7	O.P.C.	Dunbar	W.E.D.C.S.	*		5.54	5
8	O.P.C.	Dedicated Plant	W.E.D.C.S.	*		5.18	7
9	O.P.C.	Scottish Average	W.E.D.C.S.		*	5.58	14
10	O.P.C.	Dunbar	W.E.D.C.S.		*	4.65	14
11	O.P.C.	Dedicated Plant	W.E.D.C.S.		*	4.28	15
12	PBFC	Scottish Average	Glasgow	*		4.36	9
13	PBFC	Dunbar	Glasgow	*		3.64	10
14	PBFC	Scottish Average	W.E.D.C.S.	*		4.63	9
15	PBFC	Dunbar	W.E.D.C.S.	*		3.91	10
16	PBFC	Dedicated Plant	W.E.D.C.S.	*		3.61	17
17	PBFC	Dunbar	W.E.D.C.S.		*	3.33	16
18	PBFC	Dedicated Plant	W.E.D.C.S.		*	3.08	17

Contd.

Table 18 Contd.

19	PFAC	Scottish Average	W.E.D.C.S.	*		5.39	11
20	PFAC	Dunbar	W.E.D.C.S.	*		4.51	12

O.P.C. - Ordinary Portland Cement

P.B.F.C. - Portland Blastfurnace Cement (35% granulated blastfurnace slag)

P.F.A.C. - Pulverised Fuel Ash Cement (20% pulverised fuel ash)

W.E.D.C.S. - Wave Energy Device Construction Site

9. Conclusions

* The importance of cement in the overall energy inputs to wave energy systems varies with the system studied. Any reduction in the energy requirement of cement delivered to wave energy device construction sites will be of benefit primarily to devices which rely on massive concrete structures.

  An energy analysis has been performed on each of the devices being fully funded in the U.K. wave energy programme (2). The following figures illustrate the relative contribution made by the energy embodied in the cement to the total system (annual) energy input:

NEL Oscillating Water Column (Breakwater 1980)	18%
Lancaster Flexible Bag (Top Duct 1979/80)	9%
Bristol Oscillating Cylinder (1979/80)	2%

* Many values for the gross energy requirement of cements at wave energy device construction sites can be determined. The value chosen depends on the type of cement used, the cement source, and the possible energy saving technology which could be installed at some point in the future. These GER's are shown in the summary table, table 18.

* The type of cement used will depend on the acceptability of blended cement in the construction of wave energy devices. Substantial savings (>30%) in the energy input of cement to wave energy devices could be made by using Portland Blastfurnace Cement to BS 146, if this could be acceptably incorporated into device structures.

* The source of cement for wave energy devices has a bearing on the energy requirement of the cement at the device site. In the context of Scottish cement supply, Ordinary Portland cement is produced only at Dunbar in the South-East of Scotland. The remainder of the cement supplied to users is either imported as cement or as clinker which is subsequently ground to cement in Scotland. Dry process plants, such as Dunbar, are inherently more energy efficient than the wet process works more common in the U.K. Thus if all the O.P. cement supplied to wave energy devices came from the Dunbar works, savings of 17% of the gross energy requirement could be made over cement supplied from the Scottish average mix of supply.

* Further savings (of about 6%) could be made in transport energy by the use of a postulated dedicated plant located close to the wave energy device construction site. This plant however, is purely speculative and would depend on cement demand, availability of raw materials, state of the cement market and a variety of other factors.

* The maximum savings possible are by the use of a dry process dedicated plant, as above, producing Portland Blastfurnace Cement and incorporating all the energy efficient tehcnology thought likely in the near future. The gross energy requirement of this cement could be 54% less than O.P.C. from the current Scottish mix of supply.

  However, reservations are expressed elsewhere in this report about liklihood of such a dedicated plant.

* The likely maximum energy savings for cement to a wave energy device construction site using modified existing plant could be achieved by the following route. All OPC supplied from Dunbar works, converted to employ energy efficient techniques thought likely in the near future. This OPC supplied to Gartsherrie works to be ground with 35% by weight granulated blastfurnace slag. Portland Blastfurnace Cement supplied by this more likely route would achieve an energy saving of 50% over ordinary Portland cement supplied from the current Scottish mix. It must be stressed that this depends on the acceptability of Portland Blastfurnace cement to the designers and specifiers of wave energy device.

* Such savings, could have a substantial impact on the overall energy requirement of all wave energy devices. This applies especially to the NEL Oscillating Water column device which relies on a massive concrete structure for its function.

10. Recommendations

* It is recommended that Portland Blastfurnace Cement be investigated for use in wave energy device construction.

* The use of a dedicated plant could only take place if suitable raw materials exist near to proposed wave energy device construction sites. This may be a fruitful area of study, along with an investigation into the economics of such a plant.

* A simple way of improving the energetic viability of wave energy devices would be to ensure that all ordinary Portland cement supplied to their construction sites comes from a dry process plant such as at Dunbar in Lothian.

11. References

1. L.S. Martin, 'Energy Audit Series No. 11' The Cement Industry, Department of Energy/Department of Industry, July 1980.

2. G. Jenkins, 'Energy Analysis of Wave Energy Concepts, Interim Report No. 1, Lancaster Flexible Bag Device', Sunderland Polytechnic February 1981.

3. I.F.I.A.S. 'Energy Analysis, Workshop on Methodology and Conventions', International Federation of Institutes for Advanced Study, Sweden 1974.

4. D. Casper, P. Chapman and N. Mortimer, 'Energy Analysis of the Report on the Census of Production 1968', ERG 006, Open University, Energy Research Group, Milton Keynes, 1975.

5. I. Bousted and G. Hancock, 'Handbook of Industrial Energy Analysis', Ellis-Horwood, Chichester, 1979.

6. N.E.L. 'Wave Energy Study, Breakwater Device, 2GW Power Station, Reference Design 1980', Report PR22, National Engineering, East Kilbride, March 1980.

7. M.A. Smith, 'The Economics and Enviromental Benefits of Increased Use of pfa and Granulated Slag', Resources Policy, March 1975.

8. The P-E Consulting Group, 'Appraisal of Mass Production Cost for Wave Energy Devices', March 1980.

9. Price Commission, 'The Associated Portland Cement Manufacturers Limited, Increases in Cement Prices', H.M.S.O., June, 1978.

10. BS 146: Portland Blastfurnace Cement: Part 2, British Standards Institution, 1973.

11. F. Keil, 'Slag Cements', Proc. 3rd International Symposium on the Cehmistry of Cement, London, 1952.

12. F.M. Lea and Desch, 'Chemistry of Cement and Concrete', Edward Armold, London, 1956.

13. W. Gutt, 'The Use of By-Products in Concrete', Resources Policy, September 1974.

14. NATO/CCMS - 46, Industrial International Data Base, 'The Cement Industry', E.D.R.A., Oak Ridge, Tennessee, September 1976.

15. P.C. Kreijger, 'Energy Analysis of Materials and Structures in the Building Industry', 9th International T.N.O. Conference, Rotterdam, February 1976.

16. Rowe et al, 'Handbook on the Unified Code for Structural Concrete' (CP110:1972) Cement and Concrete Association (Revised edn) 1978.

17. A.M. Neville, 'Properties of Concrete', London 1973.

18. D.F. Orchard, 'Concrete Technology, Volume 1, Properties of Materials', 3rd Edition, Applied Science Publishers, Essex, 1973.

APPENDIX C

W.E.S.C. CONTRACT NO. E/5A/CON/1632/172/099

ENERGY ANALYSIS OF WAVE ENERGY CONCEPTS

INTERIM REPORT NO. 1

LANCASTER FLEXIBLE BAG DEVICE (1979 DESIGN)

FEBRUARY, 1981

G. JENKINS,

ENERGY WORKSHOP.

Sunderland Polytechnic

W.E.S.C. Contract E/5A/CON/1632/172/099 February 1981

Interim Report No. 1

ENERGY ANALYSIS OF 1979 LANCASTER FLEXIBLE BAG DEVICE

1. INTRODUCTION

This report covers the energy analysis of the Lancaster Flexible Bag (LFB) wave energy conversion device, based on information on the 'Top Duct' design contained in Wavepower Ltd., Interim Report 1979, and assessed by Rendel, Palmer and Tritton in the Consultant's Interim Report; Lancaster Flexible Bag; November 1979.

Wave energy devices are continuously changing in design in response to new ideas, model tests and wave data. To perform an energy analysis, a "snapshot" of a particular design at a particular time is required so that input and output data is consistent. This often leads to difficulties because these "snapshots", up to now, have been more than one year out of date and so the results have less impact than if the energy analysis had been performed by the device teams whilst ideas and options were being generated. The energy analysis performed here can only act as a base line from which new designs can be assessed. One of the aims of this work is to breakdown the energy analysis into categories in such a way that design changes and output reassessment can be easily assimilated into the energy analysis.

2. ENERGY ANALYSIS METHODOLOGY

Information on the energy requirements of many materials, products and processes is held at Sunderland Polytechnic (A short list of the major material energy requirements is contained in "Energy Analysis in the Assessment of the U.K. Wave Energy Programme 1978" Harrison, Jenkins and Mortimer, June 1980).

These energy requirements are usually expressed in primary energy terms (gigajoules (thermal)) $[GJ_t]$ which is a measure of depletion of the fossile fuels resource base, taking into account the conversion of these fossil fuels into secondary fuels such as electricity and smokeless solid fuel.

Net energy analysis of wave energy conversion systems is concerned with determining the direct and indirect energy inputs used to construct, operate and maintain the system. This is compared with the output of the scheme which in the case of wave energy systems is in terms of gigajoules of electricity (GJ_e) delivered to Perth, taken over a similar period. The net energy requirement (n.e.r.) of a system can be defined as:

$$\text{n.e.r.} = \frac{\text{energy input} \quad (GJ_t)}{\text{energy output} \quad (GJ_e)}$$

For a system which is viable in primary energy terms this value must be less than unity, and if used as an approximate guide to economic viability, must be much less than unity.

Wherever possible, the energy analysis is based on physical quantities for components of the wave energy system, for example the weight of prestressing strand used in the structure of the device. These are combined with energy requirements determined from process analysis, usually expressed in gigajoules per tonne (GJ_t/te). For example, the energy requirement of prestressing strand is 43.0 GJ_t/te.

However, in some instances physical data is unavailable or the process energy analysis has yet to be carried out on the materials or components involved (e.g. thyristors). In these cases recourse must be made to the costs of the items involved and the data base of energy intensities (MJ_t/£) which has been derived for all industries from the Census of Production. Unfortunately this information is not available for separate products of industries, but is the aggregate of all products of a particular industry. For wave energy devices, much of the equipment will be "specials" which will not correspond with the bulk of products in a particular sector (e.g. thyristors come in the "Radio and Electronic Components" Industry). So these energy intensities are used only as an indicator of order of magnitude, or for small inputs.

3. LANCASTER FLEXIBLE BAG ENERGY ANALYSIS

All relevant data for the 1979 Reference Design is collected together on General Data Worksheets (see example, Appendix A) Where there is vital information missing, this is determined by calculation and by consultation with the device team and consultants.

This information, in terms of tonnes of material or process energy used, or cost where this data is unavailable, is transferred to the initial Energy Requirement worksheets (see Appendix B). Here it is combined with the particular energy requirement or energy intensity of the material or process to give the initial energy input per device. This results in effect in a "first-cost" in energy terms for the device. To give an estimate of the quantity of energy which will be used in constructing, operating and maintaining the scheme over its estimated life of 25 years, this data must be expressed in a form which takes into account the relative lifetimes of each component. This is carried out on the Annual Energy Input worksheets (see Appendix C). The initial energy input per scheme is simply the initial energy input per device multiplied by the number of devices in the scheme, in this case there are 435 devices in the scheme. These are then multiplied by the reciprocal of the expected lifetime (a range is given). The reciprocal is used because it is easier to comprehend the calculation in this way, as a long lifetime will give a low value of annual energy input, a good result in net energy analysis terms.

The annual energy input per scheme gives a value of the total energy input into the scheme divided by its lifetime, so that it is in terms of equal annual amounts. Obviously, the actual situation will be very different with a large amount of energy being consumed before the device is operated, and a further substantial amount used to manufacture components for the mid-life refit. This area of study known as dynamic energy analysis could be pursued to determine the effect on national energy supply of a large wavepower installation. However, the concern of our study at this stage is to determine the basic primary energy viability of a particular wavepower scheme.

TABLE 1 NET ENERGY REQUIREMENT 1979 LFB SCHEME

ITEM	ENERGY PER 2GW SCHEME			UNITS
	LOWER	MODAL	UPPER	
Annual Energy Input	2.83	3.44	4.44	$x10^6$ GJ_t
Annual Energy Output	18.92	15.10	11.35	$x10^6$ GJ_e
Net Energy Requirement	0.149	0.228	0.390	GJ_t/GJ_e

4. RESULTS AND DISCUSSION

4.1 1979 LFB SCHEME

The annual energy input to the whole 2GW scheme consisting of 435 Lancaster Flexible Bag devices is given in the Summary Table (Table 1). This input can then be compared to the expected annual energy output from the scheme, taken from Rendel, Palmer and Tritton Consultant's Interim Report, which gives an expected power output of 0.48 GW continuous (15.1 x 10^6 GJ_e/year) per 2 GW scheme with a range from 0.36 GW (11.4 x 10^6 GJ_e/year) to 0.60 GW (18.9 x 10^6 GJ_e/year). This gives a modal value of net energy requirement of 0.228 GJ_t/GJ_e, with a probable range from 0.149 GJ_t/GJ_e to 0.390 GJ_t/GJ_e.

A breakdown into categories is given in Table 2 where the relative energy inputs are given in percentage terms. This shows that the largest inputs are in the area of device structure ('Construct Devices') and the Power Collection and Transmission Scheme, the latter being generic to all devices, being based on the system laid out in Consultants Working Paper No.18, October 1979.

The information for the 1979 device is much more thorough than in the 1978 Reference Design. Full physical information has been gathered on the General Data Sheets for device structures, tow-out, flexible bag manufacture (British Hovercraft Corporation design), air valves, moorings and pile installation so that a complete physical energy analysis has been performed on these items. The air turbines and electrical equipment on board have not yet been designed in detail for the device team, as the original 8.2 MW turbine/9MVA generator was found to be too large for the devices. Subsequently a cost only was provided for the 5.8 MW turbine/5 MW generator. More information on a physical basis is awaited on the power collection and transmission scheme, especially for the rectifier and inverter stations, which are large items, both in money and energy terms.

Table 3 shows the initial energy input for the 1979 LFB devices, along with a initial money cost per device and these are plotted on a histogram (Figure 1) in the various categories of input.

TABLE 2 ANNUAL ENERGY INPUT: 1979 2GW SCHEME (MODAL VALUES)

	ITEM	ENERGY INPUT ($x10^3$ GJ_t)	ENERGY INPUT %
1.1	Construct Devices	939.1	27.3
1.2	Construction Facility	41.8	1.2
1.3	Tow Out	120.0	3.5
2.1	B.H.C. Bag	497.4	14.4
2.2	On-Board Mechanical Equipment	242.7	7.0
3.1	Turbine	87.2	2.5
4	Electrical Generation Equip. On-Board	293.6	8.5
5	Moorings	343.0	10.0
6	Power Collection & Transmission	878.2	25.5
	Annual Input	3,443	100
	Annual Output ($x10^3$ GJ_e)	15,100	

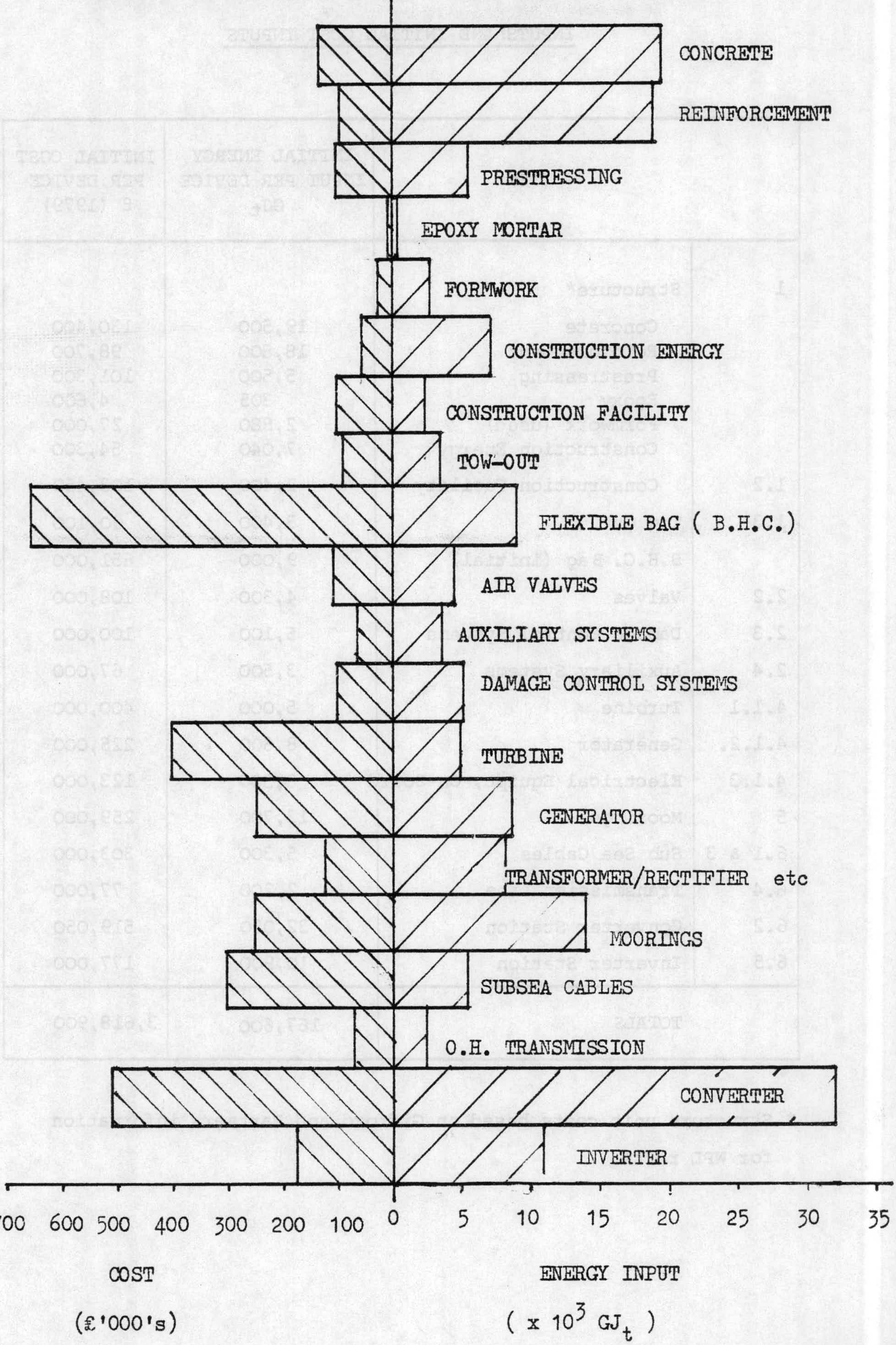
TABLE 3 1979 LANCASTER FLEXIBLE BAG - INITIAL ENERGY INPUTS AND INITIAL COST INPUTS

	ITEM	INITIAL ENERGY INPUT PER DEVICE GJ_t	INITIAL COST PER DEVICE £ (1979)
1	Structure*		
	Concrete	19,500	130,400
	Reinforcement	18,800	98,700
	Prestressing	5,500	101,300
	Epoxy	305	4,600
	Formwork (used)	2,880	27,000
	Construction Energy	7,040	54,300
1.2	Construction Facility	2,400	103,450
1.3	Tow Out	3,400	90,100
	B.H.C. Bag (initial)	9,000	651,000
2.2	Valves	4,300	108,000
2.3	Damage Control Systems	5,100	100,000
2.4	Auxiliary Systems	3,500	67,000
4.1.1	Turbine	5,000	400,000
4.1.2.	Generator	8,600	225,000
4.1.3	Electrical Equipt, On-Board	8,300	123,000
5	Moorings	13,700	259,000
6.1 & 3	Sub Sea Cables	5,300	303,000
6.4	Transmission Line	2,200	77,000
6.2	Converter Station	32,050	519,050
6.5	Inverter Station	10,900	177,000
	TOTALS	167,600	3,618,900

* Structure unit costs based on Gifford and Partners information for WPL rafts.

Fig. 1 1979 LANCASTER FLEXIBLE BAG DEVICE - INITIAL ENERGY INPUTS AND COST

INPUTS PER DEVICE



This histogram reveals some interesting points:

i) As expected, construction materials have a relatively high energy input per unit cost, reflecting their status as low added value items. As one progresses up the power chain, the energy input per unit cost decreases, as would be expected as these are higher added value items.

ii) Inspection of the energy input and 'first cost' data for the BHC Flexible Bag seems to suggest that this item has been over-costed, probably because it is a departure from current technology. The turbine also exhibits this high cost to energy function. This is because, as stated previously, only cost information was available. The energy intensity data used for turbines covers UK turbine production in 1968 which in the most part was steam, gas and water turbines for electricity generation. Air turbines are fundementally different from other types due to their operating pressures and speeds.

4.2 COMPARISON BETWEEN 1978 AND 1979 SCHEMES

An interesting comparison can be made between this study of the 1979 Reference Design and that previously carried out on the 1978 Reference Designs. This comparison is shown on a 'per 2GW scheme' basis in Table 4.

Inspection shows that the most probable (MODAL) annual energy input has risen by 30% between 1978 and 1979. However, in the same period the annual energy output has risen by 165%. This reassessment of output has offset the rise in input to give a decrease in net energy requirement 50% of the 1978 value. Thus in terms of the energy ratio* this has doubled from 2.2 GJ_e/GJ_t in 1978 to 4.4 GJ_e/GJ_t in 1979.

$$\text{* Energy ratio} = \frac{\text{energy output}}{\text{energy input}} = \frac{1}{\text{net energy requirement}}$$

TABLE 4 COMPARISON OF ENERGY ANALYSIS 1979 AND 1978 REFERENCE DESIGNS

ENERGY INPUTS AND OUTPUTS (*10^6 GJ) PER 2GW SCHEME

	1978			1979		
	LOWER	MODAL	UPPER	LOWER	MODAL	UPPER
Annual Energy Input	1.7	2.6	4.9	2.8	3.4	4.4
Annual Energy Output	9.1	5.7	2.8	18.9	15.1	11.4
Net Energy Requirement	0.19	0.46	1.72	0.15	0.23	0.39

TABLE 5 ANNUAL ENERGY INPUTS PER DEVICE (MODAL VALUES)

($x10^3 GJ_t$)

		1978*	1979
	No. of Devices in Scheme	320	435
	Lifetime of Scheme	30 yrs	25 yrs
1	Construct Devices (incl. Facility)	2.28	2.25
2	Structural Steel Components	0.03	-
3	Tow Out	0.13	0.28
4	Mechanical Components (Bag, Valves, etc.)	0.91	1.70
5	Power Take Off (air Turbine & Electrical)	1.38	0.88
6	Anchors and Moorings	1.28	0.79
7	Power Collection & Transmission	2.13	2.02
	Total Annual Input Per Device ($x10^3 GJ_t$)	8.14	7.92
	Annual Output Per Device ($x10^3 GJ_e$)	17.7	34.7

* From Table 3.2,

'Energy Analysis in the Assessment of the U.K. Wave Energy Programme, 1978' Harrison, Jenkins & Mortimer, Sunderland Polytechnic, June 1980.

Turning now to the annual energy input to a single device shown in Table 5, which has been derived by dividing the scheme annual energy input by the number of devices in the scheme, it is clear that the overall annual energy input per device has fallen by only 3%. This increase in the energy input per scheme can be partly attributed to the extra number of devices in the scheme rising from 320 in 1978 to 435 in 1979, an increase of 36%. Also in Table 5, it is interesting to note that the annual energy requirement for the structure has remained virtually unchanged. Although this is due to the alteration in the accounting lifetime of the scheme from 30 years in 1978 to 25 years in 1979. Hence the initial energy requirement for the structure has decreased by about 18% between two designs.

5. CONCLUSIONS

i) A 2GW wave energy scheme based on the 1979 Lancaster Flexible Bag device, developed by Wavepower Ltd., and Lancaster University, is viable in primary energy terms.

The annual net energy requirement* of this 1979 scheme is 0.23 GJ_t/GJ_e with a range from 0.15 to 0.39 GJ_t/GJ_e. The model value represents an energy payback period of 5.8 years with a system lifetime of 25 years.

ii) A comparison between the energy analysis of the 1979 Lancaster Flexible Bag device and that of the 1978 Lancaster Flexible Bag shows that there has been a vast improvement in primary energy viability.

The annual net energy requirement* of the 1978 scheme was 0.46 GJ_t/GJ_e.

This is due to both changes in the annual energy input needed to construct, operate and maintain the scheme, and changes in the expected annual output.

The annual energy input has risen by 30%, but this has been offset by a rise in annual energy output of 165%. The latter change is due to a reassessment of the productivity by the programme's consultants.

$$\text{* Annual net energy requirement} = \frac{\text{annual energy input } (GJ_t)}{\text{annual energy output } (GJ_e)}$$

6. FURTHER WORK

i) Certain areas of the overall 1979 scheme need more information so that an energy analysis based purely on physical quantities can be completed. The first concerns the air turbine and on-board electrical equipment, the second concerns the generic power collection and transmission system. The converter and inverter stations, which form a large energy input, need to be analysed when more detail is available. Further work is in progress on this issue.

ii) It is hoped that much of the detailed energy analysis contained in this report will be of use in performing an energy analysis for more recent designs of the Lancaster Flexible Bag device, and will be of help when considering items which are still 'on the drawing board'.

APPENDIX A

GENERAL DATA WORKSHEETS - SPECIMEN

DEVICE __LFB______ TYPE TOP DUCT_ CONCRETE_1979

GENERAL DATA WORKSHEET

SHEET 2a

DATE _6-10-80__

ITEM	VALUE			LIFETIME	SOURCE
	LOW	INTER	HIGH	RANGE	
				SYSTEM 25 yr	WPL L27
1. CONSTRUCT DEVICES				STRUCT. 30yr	WPL L27
				MAINT FREE 50yr	WPL L28
1.1 STRUCTURAL MATERIAL PER DEVICE TOTAL HULL WEIGHT		11,000 te		USEFUL 180 yr	WPL L28 WPL L102
1.1.1. CONCRETE (Grade 50)		4862 m³			WPL Private Communication 6.11.80
-CEMENT					
-AGGREGATE					
1.1.2. FORMWORK - STEEL		2000 m²			WPL private communication CP/DC/2633 6-1-81
-TIMBER per unit mould weight		2727 te			
no. of uses		1000			
-PLYWOOD					
1.1.3. REINFORCING STEEL SEE SHEET 2c		61 m³ 477 te			WPL Private Comm
1.1.4.1 PRESTRESSING STEEL SEE SHEET 2d		DYFORM 115 te (3480 m)			WPL Priv Comm
1.1.4.2 DUCTING		14 te			estimate (14-11-80)
1.1.5. STRUCTURAL STEEL		—			
1.1.6 STRUCTURE COST CURRENT		£100/te			GIFFORD LFB MEMORANDUM
DEVELOPED		£60/te			
1.1.7. PRECAST UNITS, LENGTH		10 m			RPT p25
WEIGHT EACH		500 te			RPT p25

APPENDIX B

INITIAL ENERGY INPUT PER DEVICE - WORKSHEETS

Device .L.F.B.......... Type TOP DUCT CONCRETE. Sheet I .1..

Intial Energy Input Per DEVICE. No. of Devices in .2GW.. Scheme: .4.35...

	ITEM	MATERIAL	ENERGY REQUIREMENT (or intens-ity)	Material or cost input To .DEVICE..			Initial energy input To .DEVICE..... (GJt)			Notes
				lower	Modal	Upper	Lower	Modal	Upper	
1.	CONSTRUCT DEVICES									
1.1.1	CONCRETE	GRADE 50	4.0 GJ/m^3		4862 m^3			19,448		
1.1.2	FORMWORK	STEEL FABRICATION (AMOUNT "CONSUMED")	76 MJ/m^2		38,000 m^2			2881		1000 USES OF MOULD
1.1.3	REINFORCEMENT	STEEL BAR	39.5 GJ/te		477 te			18,842		
1.1.4.1	PRESTRESSING STEEL	STEEL PRESTRESSING WIRE	43.0 GJ/te		115 te			4,945		
1.1.4.2	PRESTRESSING DUCT	STEEL	36.5 GJ/te		14 te			511		estimate
1.1.8	EPOXY RESIN	EPOXY RESIN FILLER	200 GJ/te 1 GJ/te		1.51 te 3.1 te			302 3		tak figures
1.1.10	MATERIALS TOTAL	–			–			46,932		J. Varley
1.1.11	CONSTRUCTION ENERGY	–	15% of above		–			7040		[illegible]
	CONSTRUCT DEVICES TOTAL							53,972		

Device .L.F.B........ Type TOP DUCT CONCRETE Sheet I .1...

Intial Energy Input per DEVICE..... Date 14-11-80

Device ..LFB.................. Type TOP. DUCT. CONCRETE. Sheet I 3...

Intial Energy Input Per DEVICE. No. of Devices in .2GW.. Scheme: .435....

ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE..			Initial energy input To .DEVICE.... (GJt)			Notes
			lower	Modal	Upper	Lower	Modal	Upper	
1.2. CONSTRUCTION FACILITY	*	*		—			2,400		* FROM PROCESS ANALYSIS OF 1978 DEVICES
1.3. TOW OUT & PLACE DEVICE									32 DEVICES PER YEAR
1.3.1. VESSEL FUEL									
CLYDE AREA	MARINE DIESEL FUEL		-	6.4 te*	-	-	340	—	* 3 DAYS
MAIN TOW		53,75 GJ/te	-	28.6 te(1)	-	-	1,540	—	(1) AVERAGE DISTANCE
ON-SITE			-	21.5 te*	-	-	1,160	—	* 3 DAYS
1.3.2. VESSEL HIRE	MLH 370 'SHIPBUILDING & MARINE ENGINEERING'	58 MJ/£(1979)		£7,000(2)			410		(2) 10% OF TOTAL COSTS
TOW OUT TOTAL							3,450		

Device ....LFB........ Intial Energy Input per DEVICE.... Type TOP. DUCT. CONCRETE. Date 17-11-80 Sheet I 3....

Device LFB Type TOP DUCT CONCRETE Sheet I A4 (BHC BAG)

Intial Energy Input Per DEVICE. No. of Devices in 2GW Scheme: 435

ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE lower	Modal	Upper	Initial energy input To DEVICE (GJt) Lower	Modal	Upper	Notes
2.1.1. BRITISH HOVERCRAFT Co FLEXIBLE BAG:									
2.1.1.1. MATERIALS:									
BASE FABRIC	NYLON	285 GJ/te (1)		14.2 te			4055		(1) BOUSTEAD 1979
COATING MATERIAL	CHLOROPRENE RUBBER	130 GJ/te (2)		20.1 te			2613		(2) figure for SBR RUBBER (BOUSTEAD 1979)
BOLT ROPES	STEEL WIRE	43 GJ/te		3.8 te			165		
CLAMPING BOLTS	FERRALIUM	95 GJ/te (3)		2.6 te			247		(3) assumed to be EN58 STAINLESS STEEL (MORTIMER 1980)
CLAMPING BARS	FERRALIUM	95 GJ/te (3)		11.1 te			1,054		
SEPTUM & SECTION JOINTS									
PINS & COLLARS	FASTNERS	97.9 GJ/te (4)		0.45 te			44		(4) ENGINEERING INDUSTRIES ENERGY AUDIT
WASHER PLATES	ALUMINIUM ALLOY	97.1 GJ/te		0.78 te			76		
RUBBER PROTECTORS	SBR RUBBER	130 GJ/te		0.31 te			40		
SUB TOTALS:									
7.5 YEAR COMPONENTS							6,993		
15 YEAR COMPONENTS							1,301		
MATERIALS TOTAL							8,294		

Device LFB Type TOP DUCT CONCRETE Sheet I A4

Intial Energy Input per DEVICE Date 18-11-80

Device ..LFB.............. Type .TOP DUCT CONCRETE. Sheet IA.46

Intial Energy Input Per DEVICE. No. of Devices in .2GW... Scheme: .435....

	ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE... lower	Modal	Upper	Initial energy input To DEVICE..... (GJt) Lower	Modal	Upper	Notes
2.1.1.	BHC BAG (contd)									
2.1.1.2	PROCESS ENERGY									
	AUTO-CLAVE	STEAM	3.5 MJ/kg (1)		65,000 kg (2)			227.5 GJ		(1) BOUSTEAD 1979
	STEAM HEATED PRESS	STEAM	3.5 MJ/kg (1)		32,500 kg (2)			113.8 GJ		(2) ESTIMATE
	PROCESS ENERGY TOTAL							341 GJ		
2.1.1.3	CAPITAL ENERGY									FOR 2 LOOPS (1 DEVICE) INITIAL
	BUILDINGS	MLH 151 CONSTRUCTION	33.6 MJ/£(1979)		£16,666 (3)			560 GJ		(3) assume energy accounts for 10% of capital cost. (industrial average)
	AUTOCLAVES	MLH 341/5 INDUSTRIAL PLANT	51.1 MJ/£(1979)		£833 (3)			43 GJ		
	STEAM HEATED PRESSES	MLH 339/9 OTHER MACHINERY	51.1 MJ/£(1979)		£542 (3)			28 GJ		
	BOILER PLANT	MLH 341/1 INDUSTRIAL PLANT	51.1 MJ/£(1979)		£416 (3)			21 GJ		
	CAPITAL ENERGY TOTAL							652 GJ		
	TOTALS 7.5 YR COMPONENTS							7645 GJ (4)		(4) assume all capital & process goes to [illegible]
	15 YR COMPONENTS							1301 GJ		
	BHC BAG TOTAL							8946 GJ		

Device ...LFB...... Type TOP DUCT CONCRETE Sheet IA46
Intial Energy Input per DEVICE.... Date 20-11-80

Device ...LFB............ Type TOP DUCT, CONCRETE..... Sheet I 4.C.

Intial Energy Input Per DEVICE. No. of Devices in 2 GW.. Scheme: 435....

ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE... lower	Modal	Upper	Initial energy input To DEVICE..... (GJt) Lower	Modal	Upper	Notes
OTHER MECHANICAL EQUIPMENT									supercedes I4c, 24.11.80
2.2. VALVES									* calculated from E. Audit HC, using Mortimer UK 1977 Average value for Al
2.2.1 VALVE VANES	ALUMINIUM EXTRUSION	24.1 GJ/te*		11.88 te			2863		
2.2.1 VALVE SEALING STRIPS	RUBBER (POLYCHLOROPRENE)*	144 GJ/te		1.75 te			252		* assumed
2.2.2. VALVE LINKAGES	MACHINED COMPONENTS	60.6 GJ/te		3.86 te			234		PERA.
2.3 VALVE FRAMES	STEEL FABRICATIONS	55.6 GJ/te		14.4 te			801		PERA
2.4.1 VALVE END FITTING - SHAFT	MACHINED COMPONENTS	60.6 GJ/te		1.35 te			82		P.E.R.A.
2.4.2 VALVE END FITTING - BEARING	MECHANICAL EQUIPMENT	85.5 GJ/te		0.53 te			45		P.E.R.A
VALVES TOTAL				33.77 te			4277		

Device ....LFB.... Type TOP DUCT, CONCRETE Sheet I. 4c..
Intial Energy Input per DEVICE..... Date 15-1-81

Device LFB Type TOP DUCT CONCRETE Sheet I 4d.

Intial Energy Input Per DEVICE No. of Devices in 2GW Scheme: 435

ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE lower	Modal	Upper	Initial energy input To DEVICE (GJt) Lower	Modal	Upper	Notes
OTHER MECHANICAL EQUIPMENT									
2.3. DAMAGE CONTROL SYSTEMS	339/9 MISCELLANEOUS MACHINERY	51.1 MJ/£		£100,000			5,110		INSUFFICIENT INFORMATION AVAILABLE FOR PHYSICAL ANALYSIS

Device LFB Type TOP DUCT CONCRETE Sheet I.4d.

Intial Energy Input per DEVICE Date 20-1-81

Device LFB   Type 1979 TOP DUCT   Sheet I 4e

Intial Energy Input Per DEVICE   No. of Devices in 2GW   Scheme: 435

	ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To .... lower	Modal	Upper	Initial energy input To .... (GJt) Lower	Modal	Upper	Notes
	OTHER MECHANICAL EQUIPMENT									
2.4	AUXILIARY SYSTEMS									
2.4.1	AUXILIARY POWER SUPPLY									
2.4.1.1	TRANSFORMER (100 kVA)	TRANSFORMER	20.2 GJ/m/c		1 UNIT			20.2		
2.4.1.2	AUXILIARY GENERATOR :	DIESEL ENGINE*	88.3 GJ/m/c		1 UNIT			88.3		*assumed 100 kW
	:	A.C. GENERATOR*	132.9 GJ/m/c		1 UNIT			132.9		*figure for lead-acid batteries
2.4.1.3	BATTERIES (1000 Ah)	BATTERIES	656 GJ/1000 BATTERIES		100 BATTERIES**			65.6		** assumed.
2.4.1.4	RECTIFIER / INVERTER	MLH 364 RADIO & ELECTRONIC COMPONENTS	61.7 MJ/£(1979)		£2,800*			172.7		* assumed 1/6 of cost
2.4.1.5	AUX. LOAD TRANSFORMER (100 kVA)	TRANSFORMER	20.2 GJ/m.c		1 UNIT			20.2		
2.4.1.6	AUX. DIST & SWITCHGEAR	MLH 361	66.8 MJ/£(79)		£2,800*			187.0		* 1/6 of assumed cost of AUX. POWER SUPPLY
2.4.1	AUX. POWER SUPPLY TOTAL							687		

Device LFB   Type   Sheet I 4e

Intial Energy Input per DEVICE   Date 20-1-81

Device ..LFB.............. Type 1979 TOP DUCT........ Sheet I 46..

Intial Energy Input Per DEVICE.. No. of Devices in ..2GW... Scheme: ..435...

ITEM	MATERIAL	ENERGY REQUIREMENT (or intens - ity)	Material or cost input To .... lower	Modal	Upper	Initial energy input To .... (GJt) Lower	Modal	Upper	Notes
OTHER MECHANICAL EQUIPMENT									
2.4. AUXILIARY SYSTEMS cont									* ASSUMED 1/4 of AUX SYSTEM COST
2.4.2. BILGE PUMPS	333 PUMPS VALVES & COMPRESSORS	55.8 MJ/£(1979)		£16,750*			935		
2.4.3. GENERATOR & HYDRAULIC OIL COOLING SYSTEM	333 PUMPS VALVES & COMPRESSORS	55.8 MJ/£1979		£16,750*			935		
2.4.4 TRANSFORMER/RECTIFIER COOLING SYSTEM	333 PUMPS VALVES & COMPRESSORS	MJ/£1979		£16,750*			935		
AUXILIARY SYSTEMS TOTAL							3492		

Device ...LFB........ Type TOP DUCT CONCRETE...... Sheet I.45..

Intial Energy Input per DEVICE.... Date ..20-1-81......

Device LFB Type TOP DUCT CONCRETE Sheet IA5

Intial Energy Input Per DEVICE No. of Devices in 2GW Scheme: 435

	ITEM	MATERIAL	ENERGY REQUIREMENT (or intens - ity)	Material or cost input To DEVICE			Initial energy input To DEVICE (GJt)			Notes
				lower	Modal	Upper	Lower	Modal	Upper	
3	POWER TAKE OFF EQUIPMENT ON BOARD DEVICE									
3.1	TURBINE	'TURBINES' (1)	12.5 MJ/£(1977)		£400,000 (2)			5,013		(1) from ERA ENERGY AUDIT (2) BY COST & ENERGY INTENSITY (2) MORE DATA REQD FOR FULL PROCESS ANALYSIS
3	POWER TAKE OFF TOTAL							5,013		

Device LFB Type TOP DUCT CONCRETE Sheet I.5

Initial Energy Input per DEVICE Date 25-11-80

Device ..LFB.............. Type TOP DUCT, CONCRETE.. Sheet I 6..

Intial Energy Input Per DEVICE. No. of Devices in 2GW... Scheme: .435....

ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To DEVICE... lower	Modal	Upper	Initial energy input To DEVICE...... (GJt) Lower	Modal	Upper	Notes
4.1 ELECTRICAL EQUIPMENT ON BOARD DEVICE									BY COST AND ENERGY INTENSITY
4.1.1 GENERATOR (5MW)	-	38.1 MJ/£(1979) (1)		£225,000 (2)			8561		(1) E.R.A. ENERGY AUDIT
4.1.2. TRANSFORMER/RECTIFIER	-	50.6 MJ/£(1979) (1)		£43,000 (2)			2565		(2) MORE DETAIL REQUIRED FOR FULL PROCESS ANALYSIS
4.1.3 ELECTRICAL AUXILIARIES	-	71.7 MJ/£(1979) (1)		£80,000 (2)			5740		
ELECTRICAL EQUIPMENT TOTAL							16,866		BY COST & ENERGY INTENSITY

Device ..LFB.... Type TOP DUCT CONCRETE Sheet I 6
Intial Energy Input per DEVICE.....
Date 25-11-80

Device ....LFB....................   Type TOP DUCT CONCRETE   Sheet I 8a

Intial Energy Input Per DEVICE ..   No. of Devices in 2GW .... Scheme: 435 ....

ITEM	MATERIAL	ENERGY REQUIREMENT (or intens-ity)	Material or cost input To .... lower	Modal	Upper	Initial energy input To .... (GJt) Lower	Modal	Upper	Notes
5 MOORINGS									* 12.5 yr life
MATERIALS									** 25 yr life (1) BOUSTEAD 1979
5.1.1. RODES *	PARAFIL 'A'	222 (1) GJ/te		21.2 te (2)			4706		(2) ICI DATA
5.1.2 END FITTINGS *	STEEL FABRICATIONS	55.6 (3) GJ/te		25 te			1390		(3) JENKINS 1977
5.1.3 MOORING BUOY **	STEEL FABRICATIONS	55.6 (3) GJ/te		50 te			2780		
5.3.1 PILES **	STEEL FABRICATIONS	55.6 (3) GJ/te		15 te			834		
5.3.3 PILE HEAD **	STEEL FABRICATIONS	55.6 (3) GJ/te		12.5 te			695		
5.3.4. GROUTING **	ORDINARY PORTLAND CEMENT	7.9 (4) GJ/te		24 te			190		(4) CHAPMAN 1975
MOORING MATERIALS SUB TOTAL							10,595		

Device ....LFB.... Type TOP DUCT CONCRETE Sheet I 8a ..
Initial Energy Input per DEVICE ..... Date 2-12-80 ..

Device ..LFB..................   Type TOP DUCT CONCRETE.   Sheet I 86..

Intial Energy Input Per DEVICE.   No. of Devices in .2GW.. Scheme: .435....

	ITEM	MATERIAL	ENERGY REQUIREMENT (or intensity)	Material or cost input To .... lower	Modal	Upper	Initial energy input To .... (GJt) Lower	Modal	Upper	Notes
5	MOORINGS (cont)									
5.3.2	PILE INSTALLATION									
5.3.2.1	BARGE CHARTER	MLH 370 SHIPBUILDING & MARINE ENGINEERING	58 MJ/£(1979)		£6,420①			372		① 10% OF CHARTER COST
5.3.2.1.	FUEL	MARINE DIESEL	53.75 GJ/te		48.75 te			2620		
5.3.2.3	DRILLING CUTTERS	MACHINED COMPONENTS	60.6 GJ/te		0.5 te			30		PERA Report
	MOORINGS INSTALLATION SUBTOTAL							3022		
	MOORINGS TOTAL							13,617		

Date 2-12-80

Device LFB.................. Type TOP DUCT CONCRETE.. Sheet I10...

Intial Energy Input Per DEVICE. No. of Devices in 2GW... Scheme: 435....

ITEM		MATERIAL	ENERGY REQUIREMENT (or intens - ity)	Material or cost input To SCHEME			Initial energy input To DEVICE..... (GJt)			Notes
				lower	Modal	Upper	Lower	Modal	Upper	
6	TRANSMISSION									FROM CONSULTANTS WORKING PAPER 18a
6.1	MVDC CABLES	35 KVDC CABLE	525 GJ/km ①		3050 km			3700		① FROM RATIO OF COSTS MV/HV
6.2	CONVERTOR STATION	MLH 364/1 RADIO & ELECTRONIC COMPONENTS	61.7 MJ/£1979		£226 M			32,050 ②		② BY COST & ENERGY INTENSITY MORE DETAIL REQUIRED
6.3	HVDC CABLES	250 kVDC CABLE	1750 GJ/km ③		400 km			1609		③ FROM COOK STRAIT CABLE DATA
6.4.	HVDC OVERHEAD LINES	250 kVDC.	3400 GJ/km ④		280 km			2190		④ FROM 1978 Report No. 18.
6.5	HVDC INVERTER (METHVEN)	MLH 364/1 RADIO & ELECTRONICS COMPONENTS	61.7 MJ/£(1979)		£77 M			10,900 ②		
	TRANSMISSION TOTAL							50,449		

Device ..LFB......... Type TOP DUCT..CONCRETE.. Sheet I 10..

Intial Energy Input per DEVICE.... Date 4-12-80..

APPENDIX D
(WESC(81)P 591)

ENERGY ANALYSIS AND THE UK WAVE ENERGY PROGRAMME

PRESENTATION TO THE WAVE ENERGY STEERING COMMITTEE

by

R. Harrison

and

G. Jenkins

(Sunderland Polytechnic)

June 1981

The use of energy analysis

1. We are interested in the economics of energy technologies and in particular the relationship between the physics and engineering of a technology and its economics. It is our view that energy analysis gives a useful guide to economics but our experience is that this depends very much upon the context of the study. For example let us compare low enthalpy geothermal systems with fusion, both being areas in which we are currently doing work.

2. The technology associated with geothermal systems is well known; low enthalpy systems are operating and the hardware costs can be forecast accurately. However, drilling contains a high risk element and this limits the overall accuracy of the costing. Additionally the economic prospects depend upon the geographical relationship between resources and markets and, in the UK, on the way in which the onland drilling market will develop, together with its rate of inflation relative to rising energy prices. The critical factors tend to be related to markets rather than physics and engineering and energy analysis can make little contribution. The contribution which can be made is in the forecasting of ultimate resource limits and the effects of factors like reservoir permeability on these. We see energy analysis as interesting but not vital to the study.

3. Fusion is in a different category; it is difficult to forecast hardware costs because of the many unknowns associated with the technology. Designs do exist from which inventories of materials, machines etc., can be complied but, because no really comparable systems have been built, there is nothing upon which to base a precise costing. Culham are costing Tokamaks using the experience of fission (PWR and AGR) station costs but experience has shown the difficulty of forecasting the costs of these stations themselves. Without really comparable analogies for which costs are available the process of estimating the costs of a new technology must be hazardous. We consider wave energy technology to be largely in this category.

4. However, in a situation where costs are unavoidably uncertain, criteria are still needed upon which to base R & D decisions. We argue that energy analysis provides an indicator which can be used in these circumstances to screen avenues of development and identify those which may be fruitless.

Energy Analysis, absolute physical limits and economics

5. The basic minimum criterion for viability of any new source of energy is that it must be capable of delivering more energy than is consumed in its manufacture and operation. In order to apply this simple idea to real systems it is necessary to lay down conventions by which energy inputs and outputs are compared. It is inappropriate to set out these conventions in detail here but some simple cases will be discussed later by way of illustration.

6. We define a net energy requirement (NER). This is the ratio of all purchased fuel inputs for construction and operation (but not including at any stage the resource energy which is being processed or converted by the technology) to the total amount of saleable fuel output. The net energy requirement is a parameter which reflects basic viability.

7. The viability of energy technologies is limited by physical parameters i.e. there must be absolute physical limits to the diffuseness and the variability of an energy source below which it would not be viable to develop a technology to extract the energy. For instance, we might agree, to take ridiculous examples, that moonlight and the kinetic energy of snow flakes would be well below the absolute physical limits of viability. On the other hand highhead hydro-power installations, which have been thoroughly tested in the energy market, must be well above this limit.

8. Doubts arise about new technologies which have not been thoroughly tried and tested in the market. Some may have real prospects of economic viability now or in the medium term but equally some technologies (or combinations of technologies and locations) may lie close to the physical limits and not have these prospects. It would seem to be important to have early identification of these technologies so that they can be eliminated thus saving R and D resources.

9. In the case of wave energy the parameters of prime importance are:-

(a) power density (kW/m), which determines the scale of device structures required, and

(b) the pattern of power availability, which determines the average load factor for utilization of machinery and transmission equipment.

The net energy requirement is sensitive to the power density and to the availability of the energy source (through the scale of the structure and the machinery utilisation respectively). Hence it is natural to identify the minimum criterion for viability (NER = 1) with absolute physical limits.

10. This brings us to the basic question: Do the present devices in the wave energy programme lie close to the absolute physical limits of viability? Earlier work on the 1978 reference designs indicate that this may be so and prompted the suggestion that it may never be possible to identify a viable device. If current studies support these misgivings, the future of the wave energy programme in its present form must be seriously questioned.

Methods of Energy Analysis

11. There are a number of ways in which the energy inputs and outputs can be accounted and there will be confusion if comparisons are not made on a consistent basis. Confusion often arises in comparing a simple single stage conversion technology with a two stage system. Wave energy is an example of the former, a simple case of conversion of mechanical to electrical energy; a combination of a coal mine and coal fired power station is an example of a two stage system, coal being mined and then converted to electrical energy. Confusion arises over the accounting of the coal on its way from mine to power station. Consider the two cases in turn.

12. Let us consider the single stage conversion of a resource. In the cases of wave and wind resources the single stage conversion results in electrical output; in the case of coal, uranium, wood etc. the single stage conversion results in a pile of fuel for burning. The energy inputs and outputs are shown in Figure 1.

E_1 is the resource energy; i.e. the energy available in the waves, the coal in the ground etc.

E_2 is the input energy purchased from the external energy economy to fabricate machines, construct facilities and operate the processes; it has money associated with it and depends upon the quantities of materials required to implement the technology.

E_2 is the energy output for sale to the energy economy.

Consider the significance of ratios of these quantities:

E_2/E_1 reflects the relationship between the scale of operations necessary to extract energy and the energy density of the resource. It is a ratio of inputs and as such it does not reflect in any way the effectiveness of the technology in converting the resource to a useful fuel output.

E_3/E_1 on the other hand is an efficiency figure reflecting the effectiveness of the technology in converting the resource to a fuel (productivity). However, it does not include any quantities which relate to the scale of the technologies.

E_2/E_3 reflects the relationship between the scale of the technologies (through the input energy E_2) and their output.

13. This quantity E_2/E_3 is called the net energy requirement. It can be associated with the physical limits of viability and, because the energies E_2 and E_3 are associated with money transactions, it can be used as an indicator of economic viability. This is discussed further in paragraph 18.

14. Let us consider a two stage conversion system. Examples of these are coal, oil and uranium which are mined, processed and transported to a thermal power station where they are converted to electricity. The energy inputs and outputs are shown in Figure 2.

E_1 is energy in uranium ore, coal or oil in the ground;

E_2 again represents purchased energy required to implement the extraction and processing technologies;

E'_1 represents the energy in the intermediate fuel e.g. refined oil, washed coal, enriched uranium;

E'_2 represents purchased energy required to construct and operate the power station but does not include the energy in the intermediate fuel;

E_3, as before, represents the energy sold as output.

15. A number of quantities can be defined. We can define

- the efficiency of the first stage as $(E'_1)/(E_1)$
- the efficiency of the second stage as $(E_3)/(E'_1)$

  (it is this number, the thermal efficiency of the power station, which naturally comes to mind.)

- an overall efficiency $(E_3)/(E_1)$

- an overall net energy requirement $(E_2 + E'_2)/(E_3)$

E'_1 the energy content of intermediate fuel is internal to the overall system and so does not appear in the NER.

16. Comparing the single stage conversion technology with the two stage system it would be consistent to compare.

	SINGLE STAGE	TWO STAGE FIRST	TWO STAGE SECOND	TWO STAGE OVERALL
• Efficiencies	$\frac{E_3}{E_1}$	$\frac{E'_1}{E_1}$	$\frac{E_3}{E'_1}$	$\frac{E_3}{E_1}$
• NER	$\frac{E_2}{E_3}$	$\frac{E_2}{E'_1}$	$\frac{E'_2}{E_3}$	$\frac{(E_2 + E'_2)}{E_3}$

The figures for efficiencies would all be less than 1 in varying degrees; for viable technologies the NERs should be very much less than 1. It is clearly inconsistent to compare the net energy requirement of a single stage system E_2/E_3 with the efficiency of the second stage of a two stage system E_3/E'_1.

17. Comparative energy analyses of wave energy and thermal power stations can be carried out. The results obtained are perfectly consistent and consistently relate to the economics of the two systems. There are no paradoxes and no methodological problems. However, the fossil fuel fired thermal stations is not the best case with which to compare wave energy from the energy analysis point of view. Some better examples are given in paragraphs 23-26.

Relationship between Energy Analysis and Economics

18. The fact that a technology has a net energy requirement of less than one is merely an indication that it is within the absolute physical limits. It provides no indication as to economic viability. Indeed it would be expected that for economic viability a technology would need a net energy requirement substantially less than 1. It is not easy to decide exactly what upper limit of net energy requirement should be associated with the limits of economic viability but the following argument is one which is often used in this connection.

19. A minimal criterion for economic viability is that the total value of energy produced should equal total costs i.e. just break-even. Using the notation given in Figure 3, V = C. This break-even criterion is minimal in that no account is taken of the time relationship between costs and

earnings. A detailed analysis shows that its validity depends upon the relationship between the discount rate and rate at which the value of the output energy rises in real terms. In the situation where these two rates are equal then the break-even criterion is essentially valid. In the situation where the discount rate is greater than the rate at which the value of the output energy rises in real terms a more stringent economic criterion would be required. In this situation economic viability would require the total value of fuel produced to be greater than total costs by at least some factor greater than one. The break-even economic criterion then presupposes that the technology will operate in favourable economic circumstances. Hence applying the break even criterion to new technologies will represent their economic prospects optimistically.

20. Let us now consider how the break-even criterion can be transformed into a net energy requirement criterion. Consider a single stage conversion system and suppose that it is just economic in terms of the break-even criterion. The energy quantities are shown in Figure 1 and the costs and the benefits are depicted in Figure 3. The quantity of energy required to construct and operate the plant is E_2 and the quantity of energy output is E_3. If P_2 and P_3 are the cost per unit of input and output energy respectively, then P_2E_2 is the financial cost of the energy input and P_3E_3 is the financial value of the output energy. On average the energy element in industrial costs is in the region of 10% of total costs. Hence, in this particular case where total costs equal the value of output energy we expect the energy element in the costs to be equal to about 10% of the total value of the output energy i.e.

$$P_2E_2 = 0.1 \times P_3E_3$$

21. In the simplest case where the cost per unit of input energy is approximately equal to the value per unit of the output energy ($P_1 = P_2$) then

$$E_2 = 0.1 E_3$$

or

$$E_2/E_3 \quad \text{(Net Energy Requirement)} = 0.1$$

In other words even if a technology satisfies only the break-even economic criterion it must have a net energy requirement of no greater than 0.1. A more stringent economic criterion would have the effect of lowering the corresponding upper limit of the net energy requirement.

Some Comparative Cases

22. Solar cells and fusion power are taken here because we have done work in these areas and they illustrate well the range of results which can be obtained and the implications which arise from them.

Terrestial Solar Cells

23. There are many solar cell technologies based on different materials and fabrication techniques. Those based on silicon slices have been successfully applied in the field of space technology and although the costs are very high the value of the output is correspondingly high because there are no alternative fuels. The problem is to reduce the costs to a level at which this type of solar cell can operate economically in the context of a

general energy supply system. Here the value of the output will be much lower and will be related to the normal cost of competing fuels. In this case economic arguments of the kind outlined in the previous section can be applied and energy analysis can make a useful contribution. A number of energy analysis studies have been carried out in the silicon solar cell field and for single crystal sliced silicon the results give net energy requirements in the region of 1 in favourable locations. This is not hard to understand. Single crystal silicon is an energy intensive material and the process of slicing is wasteful, the yield is low and difficult to improve. The energy analysis clearly identifies the problem as one of materials economy which, for single crystal silicon, is difficult to solve. It is unlikely that further R and D will overcome this quickly.

24. On the other hand thin film cells formed by vapour deposition, sputtering or chemical deposition are generically different from silicon cells and do not suffer from the same limitations. We have carried out analyses of Cu_2S - CdS sputtered cells. In this case although the production system can be specified actual production costs are difficult to estimate as they depend on the costs of large vacuum systems and production experience of long runs of cells. However, our calculations indicate that net energy requirements less than 0.1 are possible. The materials energy input to the spluttered cells is small, the major energy requirement being in the manufacture and operation of the vacuum stations.

25. Comparing these two cases we see that the silicon single crystal cells, with great problems of materials economy, are at the absolute physical limits of viability making the possibility of eventual economic viability remote. On the other hand the CdS sputtered cells, which are free of the materials problems, are well on the right side of the absolute physical limits and could become economically viable through the careful application of production engineering.

Tokamak Fusion Reactor

26. Although many problems of the physics and engineering of fusion reactors remain unresolved, designs for reactors do exist from which quantities of materials can be estimated. Magnetic containment fusion devices of the Tokamak type have relatively low power densities of 1-10 MW_{th}/m^3, compared with about 100 MW_{th}/m^3 for a fission reactor. The scale of the structure is related to power density and as fusion reactors employ large amounts of special materials it is quite possible that they may be close to physical limits of viability. However, calculations we have just completed indicate an energy input figure in the region of 28×10^{15} J for the construction of a fusion reactor power station; if this is compared with an estimated energy output of 6×10^{17} J, a net energy requirement of 0.045 is indicated. We conclude from this that fusion reactors lie well within any absolute physical limits and there appears to be no inherent barriers to eventual viability. Further energy analysis is probably redundant in this case.

Energy Analysis of Wave Energy

27. Our calculations of net energy requirements for 1978 reference designs are shown in Figure 4. We are currently carrying out further calculations to reflect the state of devices in 1979 and through discussions with device teams are incorporating the results of latest developments. In this way we are building up a progressive picture of the development of the devices.

Salter DUCKS and S.E.A. CLAMS

28. Updated calculations are currently being carried out on these devices but no results are yet available.

Bristol Cylinder and Oscillating Water Columns

29. To date, calculations show that these devices have an NER in the range 0.57-1.05. Whilst trying not to anticipate future results, the indications are that continued development will have little impact on the size of energy inputs for these devices. The NERS are changing somewhat through reassessments of productivity but are not departing markedly from unity. This is the same region as the sliced silicon solar cell discussed earlier and similar conclusions would be valid. These would be that these devices are too close to the absolute physical limits, too much material and too many machines are required for them ever to be viable.

Lancaster Flexible Bag

30. The Lancaster device has an NER significantly less than 1. Its characteristics (and, by generic analogy, those of the CLAM) set it significantly apart from the other devices and indications are that it has a much greater chance of success. However, before this conclusion can be reached we must be sure that the predicted performance for the LFB is confirmed i.e. its productivity is as firmly based as for the other devices. It must be stressed that the productivity of all the devices is critical in our calculations.

31. However pessimistic the findings presented here appear, the development of solar cells should be borne in mind; new wave energy concepts should be sought which are generically different to the current devices and which offer similar prospects for improvement which the CdS cell offers over the single crystal silicon cell.

FIGURE 1

a) Single Stage Case

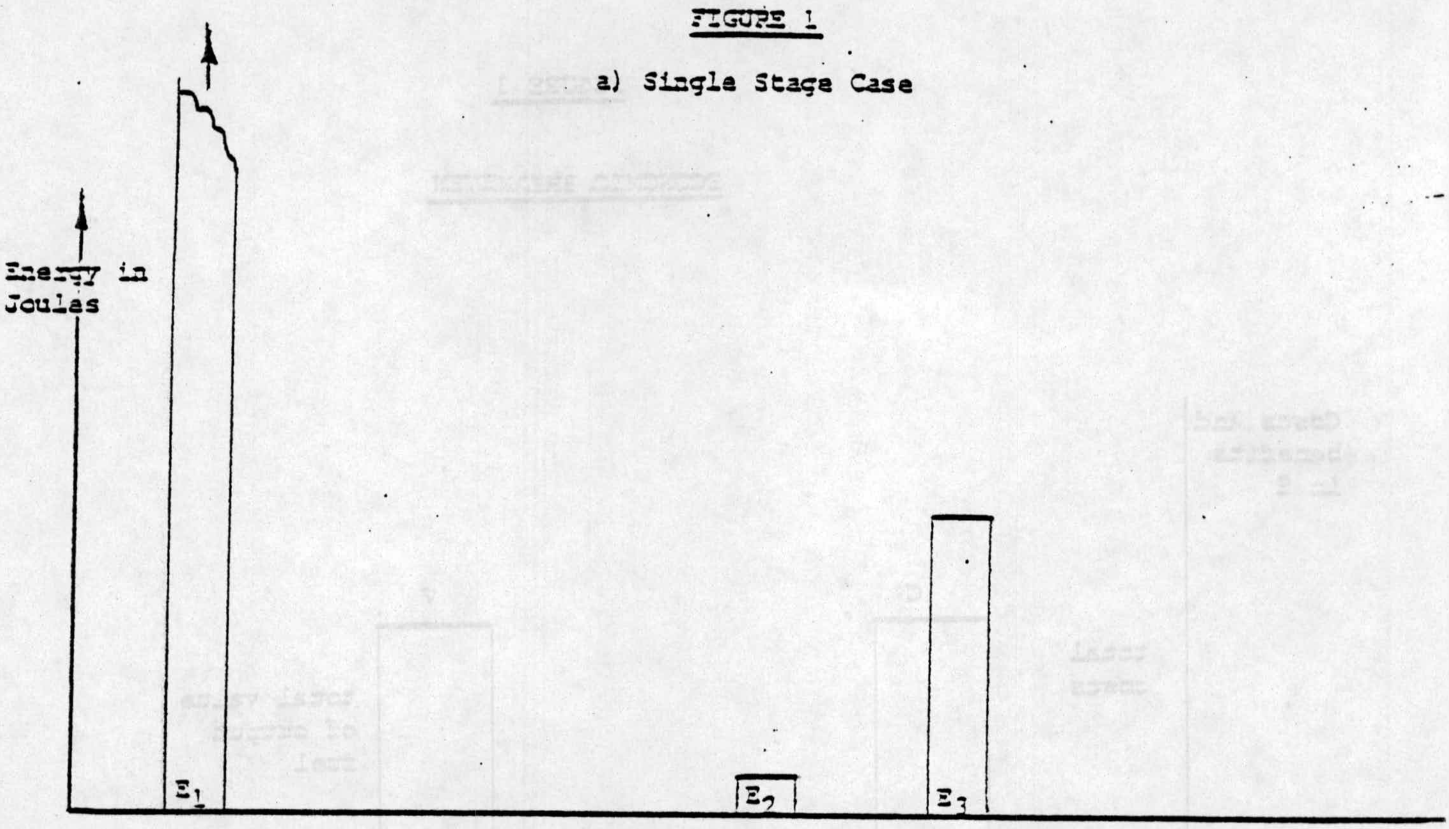


FIGURE 2

b) Two Stage Case

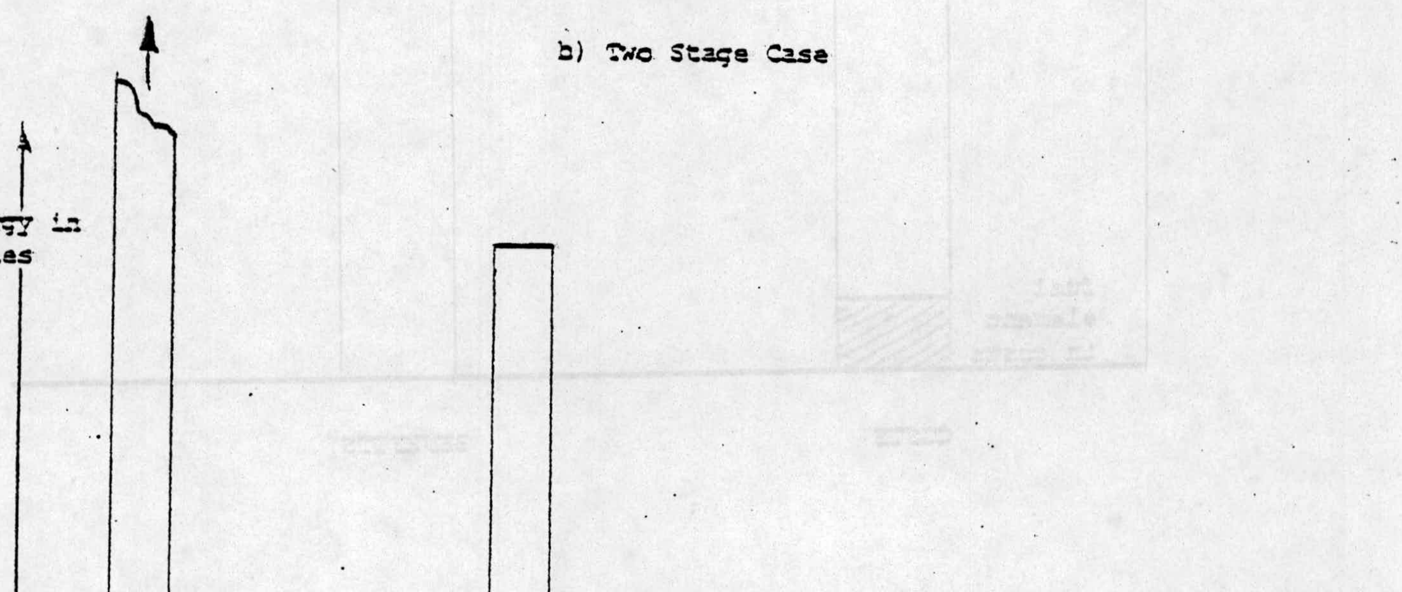
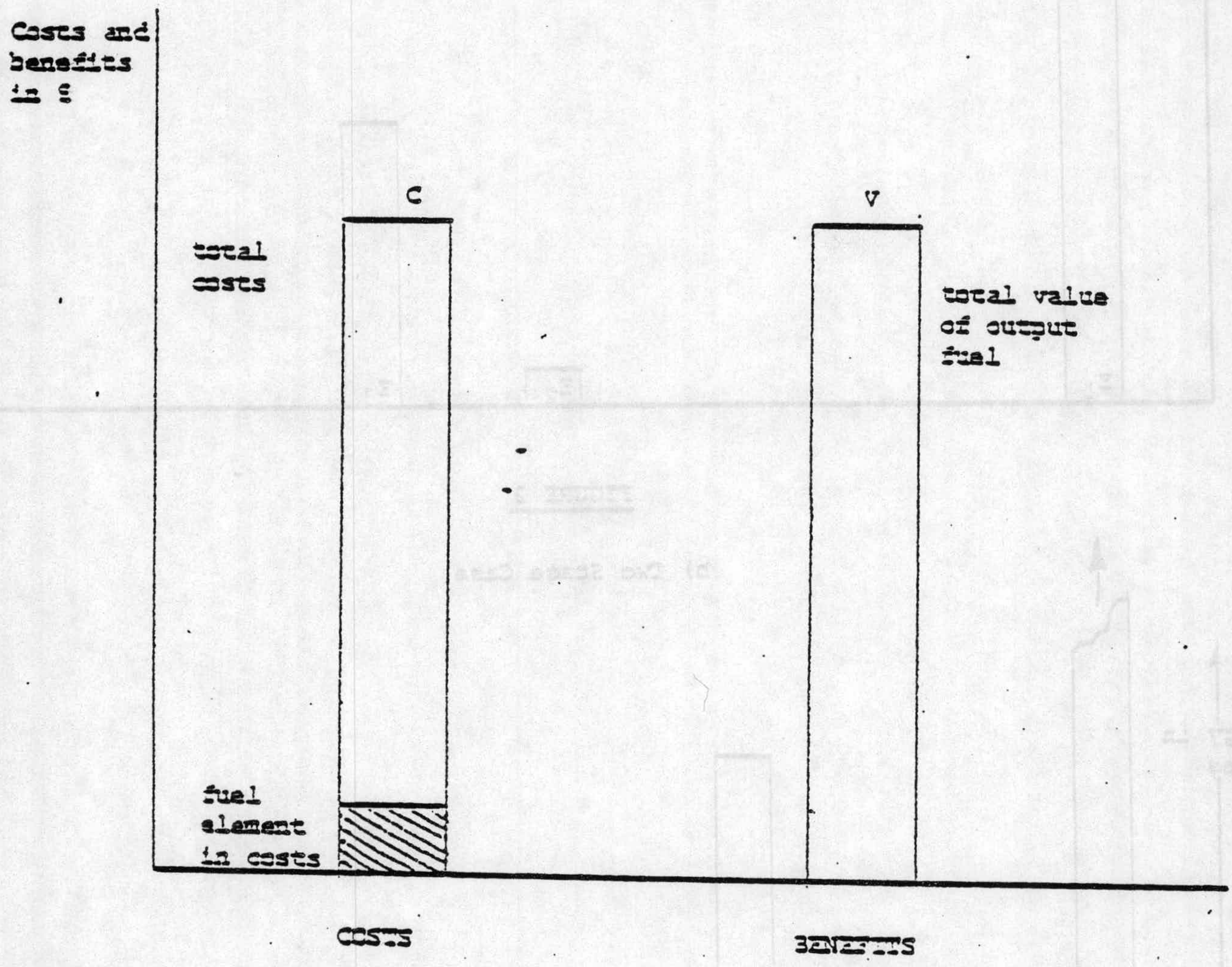


FIGURE 3

ECONOMIC BREAKEVEN



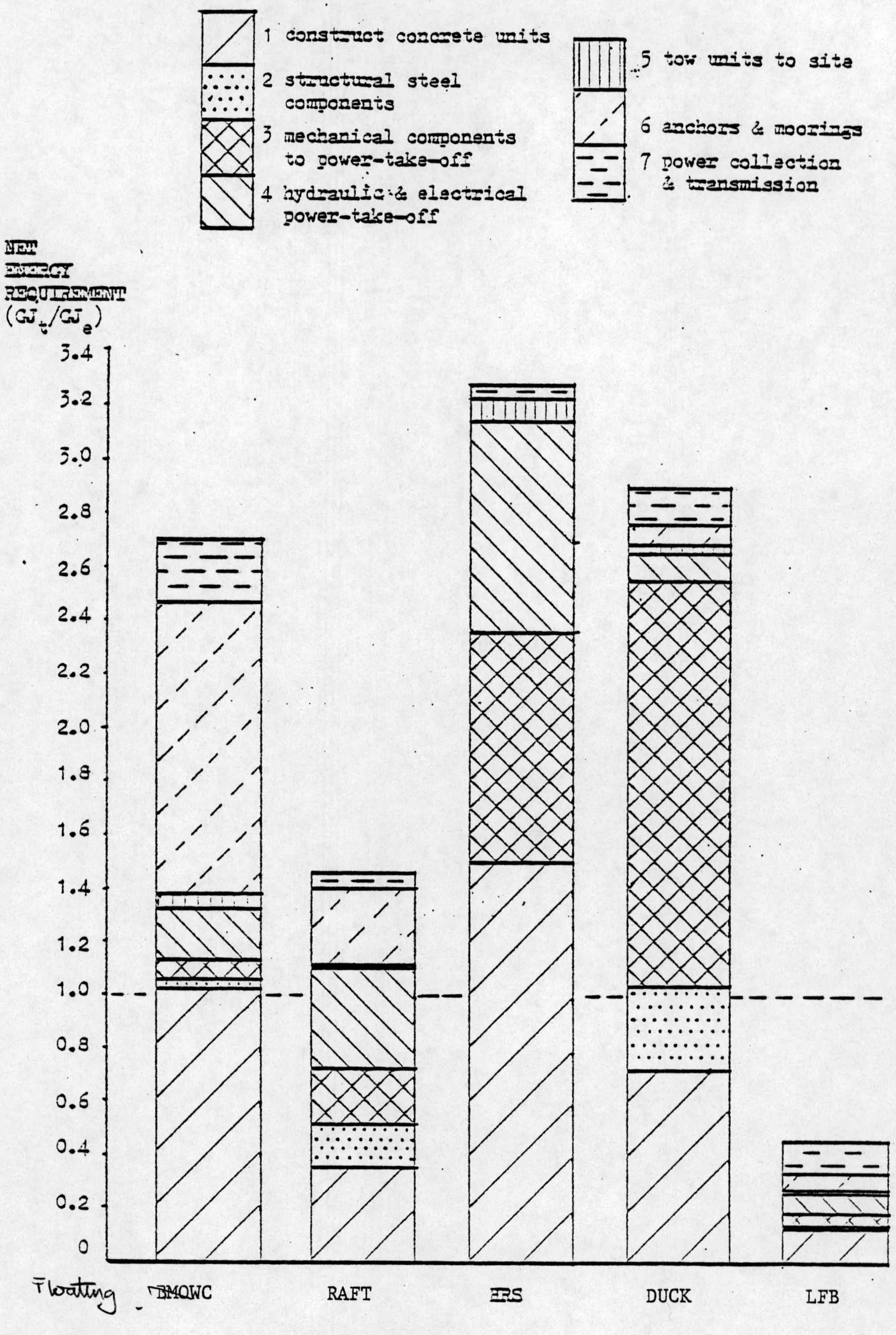


FIG 4 NET ENERGY REQUIREMENTS OF WAVEPOWER SYSTEMS

SUNDERLAND POLYTECHNIC

Note on the Comparison of Wave Energy Conversion Systems with Fossil Fuel Fired Thermal Power Stations Using Energy Analysis and Economics.

Figure 1 shows in parallel the costs and the energy analysis of a hypothetical wave energy station which is economic in the sense defined by criterion that total costs just equal value of output. The same parallel analysis for an equivalent fossil fuel fired thermal station producing the same output is also shown. It is supposed that the wave energy station can match the versatility of the thermal station and that the electricity produced is as valuable as that produced by the thermal stations. The diagram is constructed in the same way as those in the presentation and the notations are similar so that EW_1 and EM_1 are the energy in the waves and in the mine respectively.

EW_2 is the energy required to construct the wave energy station.

EM_2 is the total purchased energy required to construct and operate the mine.

EP_2 is the total purchased energy required to construct and operate the power station.

This wave energy system is just economic so that the net energy requirement (EW_2/EW_3) is in the region of 0.1. Similarly the combined mine and thermal station has an overall net energy requirement ($EM_2 + EP_2)/EP_3$) of about 0.1.

Also for the wave energy system, the quantity of output electricity is only a fraction of what is available in the waves and we may expect EW_1/EW_3 to be in the region of 5. Similarly for the combined mine and thermal station, the quantity of coal supplied to the power station is 3 or 4 times the output but the mine is only 60-80% efficient in extracting coal in the ground hence EM_1/EP_3 would be in the region of 5. There are no inconsistencies here, no paradoxes, no problems for methodology. There is a major difference between the economics of the two systems if we compare the wave energy system with the power station alone. The fuel element in the costs of the wave energy system is very small, but for the thermal station the majority of the costs can be accounted to coal supply.

Figure 2 shows the comparison between a wave energy station with a net energy requirement of 1, with an economic fossil fuel fired thermal station producing the same output. The energy in the waves and in the mine is left out to simplify the diagram.

For the wave energy system, the fuel element in the costs corresponding to the purchase of EW_2 is a small element in total costs, and the total costs are several times the value of the output.

For the fossil fuel fired station the costs accounted to the supply of fossil fuel are the major element in the costs of the electricity output. It is tempting to focus attention on the fossil fuel inputs only; EW_2 for the wave energy case and $EP_1 + EP_2 + EM_2$ for the thermal case. Granted the overall fossil fuel inputs in the wave energy case are smaller than those input to the fossil fuel system. So if all other costs were trivial compared with fossil fuel costs then the wave energy system would be preferred. However, this is by no means the case nor is ever likely to be.

Costs accounted to fossil fuel supply are a major element in the fossil fuel system but are only a minor element in the costs of the wave energy system. The energy inputs to the wave energy system would have to be greatly reduced (with total costs following) before the economic comparison can favour wave energy. This is essentially what we have been saying since 1978: it is the purpose of this note to demonstrate that this conclusion is not invalidated in any way by misleading comparison with fossil fuel fired thermal stations.

Figure 1 ECONOMICS & ENERGY ANALYSIS OF SYSTEMS SATISFYING COSTS = BENEFITS BREAKEVEN CRITERION

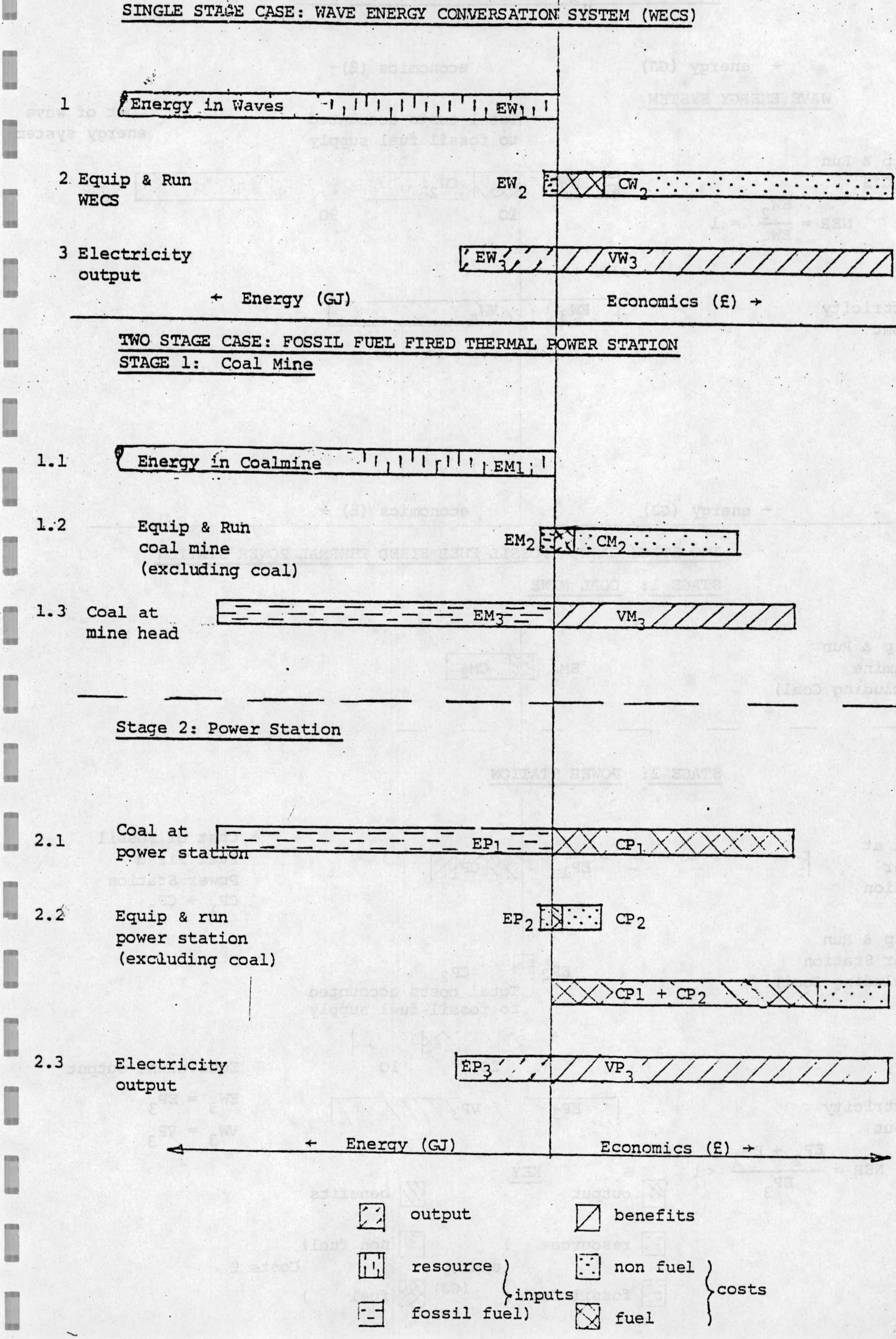
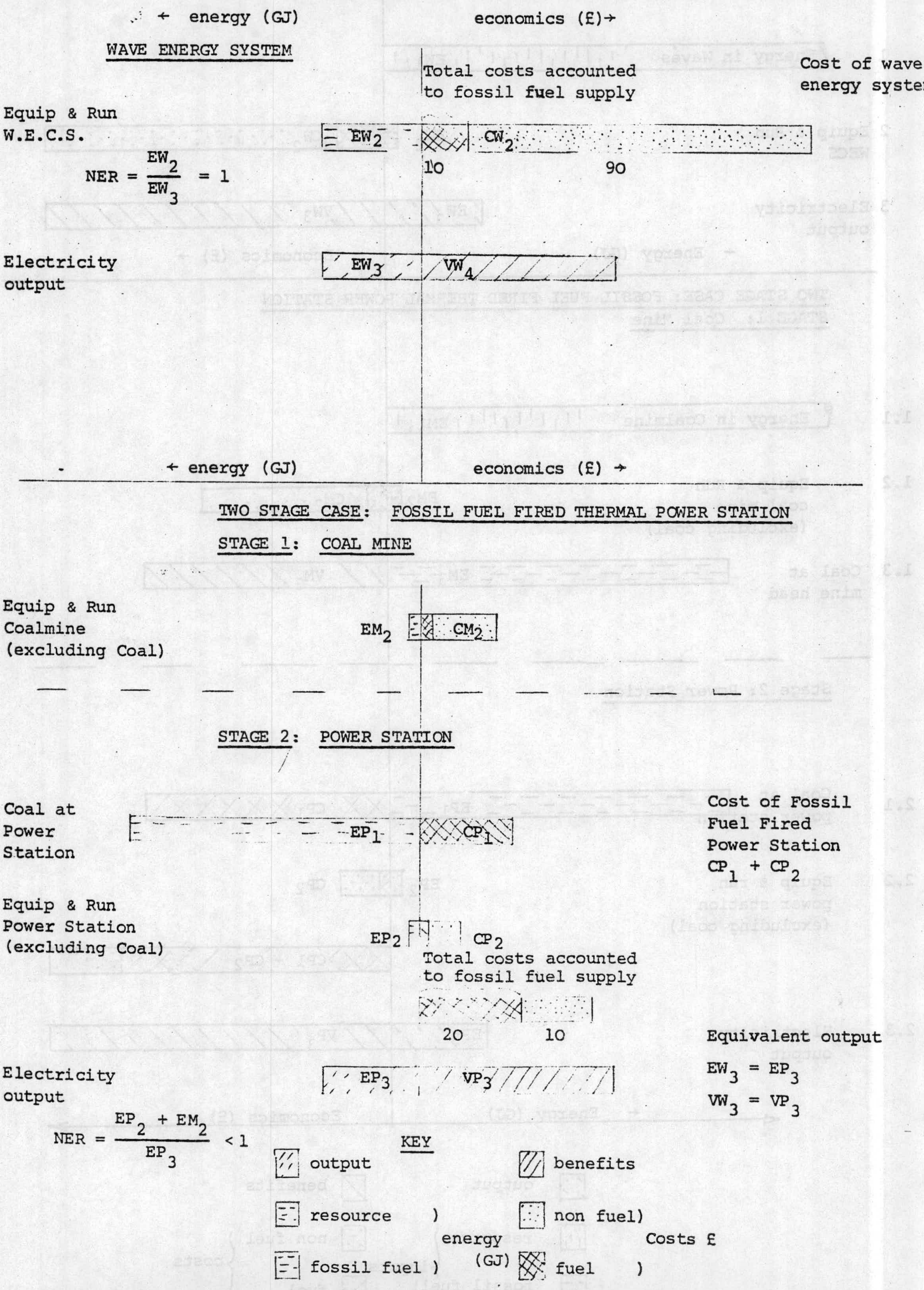


FIGURE 2 COMPARISON OF WAVE ENERGY SYSTEM WITH NET ENERGY REQUIREMENTS OF 1 WITH A FOSSIL FUEL FIRED POWER STATION WITH EQUIVALENT ELECTRICITY OUTPUT.



APPENDIX E

WESC CONTRACT No. E/SA/CON/1632/172/099

DESIGN CRITERIA FOR WAVE ENERGY SYSTEMS;

MAXIMUM RESOURCE EXPLOITATION VERSUS MINIMUM UNIT COSTS

R. HARRISON,

G. JENKINS.

AUGUST 1981

1. Introduction

The purpose of this paper is to discuss the principles underlying the optimization of wave energy systems. It is shown that there are two main optimization criteria which can be used.

a) Optimization to extract a high fration of the available resource.

b) Optimize to produce electricity with minimum unit costs without regard to size of the resource utilized.

It is likely that these criteria are mutually exclusive. A procedure is outlined by which wave energy systems can be optimized to give minium unit costs.

It is suggested that studied of this type should be an essential part of the wave energy programme and could form the basis of a prototype design study.

2. General Principles

From the outset of the development of wave energy emphasis has been placed on the size of the resource available and the contribution which could be made to U.K. supply.

This stress laid upon the size of the resource has probably had profound implications for the design philosophy of device teams and may in part have resulted in the high unit costs which are being reported.

It is useful to examine this emphasis in the context of the general procedure of energy resource assessment. When an energy resource is being assessed for possible development the normal sequence of studies is:

a) Physical assessment of the size and characteristics of the resource. In the case of wave energy this involves climate scattergrams of the distribution of power available over the spectrum of sea states encountered at the site. For a wind power site it is necessary to determine wind speeds, directions and their frequencies of occurence throughout the year. For an oil reservoir the size of the reservoir, theformation pressure, rock porosity and oil viscosity are all important parameters. This stage is followed by:

b) An engineering study of the technical problems of extraction and conversion of the resource. Here the important issue is to achieve a technical solution within a given set of economic constraints and an important parameter in this choice of technology is the fraction of energy in the resource which it is feasible to extractor convert. In general it is possible to define a combination of technology which will extract some fraction of the resource at minimum units costs. A higher fraction of the resource can be exploited by adopting a modified technical solution with higher unit costs. For example, Putnam (5) has set out a procedure for designing a wind energy generator for any particular site which produces electricity with minium unit costs. The procedure is summarised by the curves shown in Figure 1, where it can be seen that the area occupied by all possible devices is bounded by a minimum cost envelope. A larger scale design with a higher tower, longer blades and a larger alternator would exploit a larger fraction of the wind energy resource at the site but at the expense of higher unit costs. The same general principles could also apply to an oil field development. Initial production driven by formation pressure will result in minimum unit costs. Reinjection of gas into the top or the pumping in of brine in to the bottom of reservoir will increase the fraction extracted but at higher unit costs, as also will, finally, the variety of methods of secondary production.

It is normal with a new technology like wind or wave energy, or with a new oil bearing province for example; to begin development in an economically cautious way by extracting those elements of the resource which can be won at minimum unit costs. The development can be extended to higher unit cost elements as this becomes justified by experience with the technology any by economic circumstances. It is interesting that wind power developments are following this pattern. The first MW machine is being built in Orkney where the wind regime is energetic and the value of the output will be high (do we know that it has been optimized in the Putnam manner for this location?) the emphasis being on a cost effective solution to a local need rather than a large scale contribution to U.K. supply.

In the wave energy programme, however, as the initial paragraphs have shown, the normal process of cautiously developing the minimum unit cost elements of the resource first is not being followed. The programme has aimed, at the outset, at a high level of resource exploitation. This has led device teams inevitably in the direction of large, highly rated devices, which are sited well offshore. It is this type of technical combination which has been studied almost exclusively, the result being that although a great deal of work has been done to reduce the unit costs of these high resource exploitation systems, little work has been done to investigate designs which would reduce unit costs at the expense of reduced resource exploitation. This is despite indications which have periodically been given that this could be possible (1, 2, 3, 4).

Work needs to be done to identify the minimum cost envelopes of wave energy devices in the same way that Putnam has done for wind energy converters.

It is possible that three aspects could be worth investigating in this respect. These are:

1. Device size,
2. Machinery rating,
3. Distance offshore of device sitings.

2.1 The Variation of Captured Power With Device Size

Using RPT notation and the formulae developed by them, the captured mechanical power of a device P_{capij} operating in a sea state characterised by a significant wave height H_{sj} and energy period T_{ei} is given by:

$$P_{capij} = P_{seaij} \, \overline{\cos\theta} \, \eta_{ij}$$

where P_{seaij} is the power available in the sea state ij

$$P_{seaij} = n_{oij}\, \rho g^2 / (64\pi)\, (H_{sj})^2\, T_{ei}$$

(n_{oij} is the fractional occurrence of the sea state H_{sj}, T_{ei} in the year)

Cos Θ is the directionally factor of the particular device configuration and η_{ij} is the 'sea efficiency' of the device in the sea state ij. η_{ij} depends upon the device size and upon its hydromechanical characteristics, the values of η_{ij} are either measured in tank tests or inferred from tank tests on the device models.

The annual power captured by the device is the sum of all of the values of P_{capij} over all of the sea states encountered in a year.

$$P = \text{Cos}\ \Theta \sum_{i=1} \sum_{j=1} P_{seaij}\, \eta_{ij}$$

It can be seen from this that $\underline{P}$ depends upon device size and characteristics through η_{ij} and upon the details of the wave climate at the location. Because the frequency of occurrence of the sea states ij affects the values of P_{seaij} and these will vary from location to location.

In one given location the captured power might vary with characteristic device dimension in the way shown in Figure 1. Because of the programme emphasis on the size of resource which is made available device teams tend to choose large devices in the region of A in Figure 1. If the variation in structural costs as a function of characteristic size is known then it is possible to determine the unit costs of captured power. If this is done it is possible that a different value of characteristic device dimension will be indicated.

Salter Ducks may provide a simple example of this, the structural costs of large ducks may rise in proportion to the square of duck stern diameter, while small ducks may have high fixed structural costs to ensure survival. If these considerations are valid structural costs may vary with duck stern diameter in the way shown schematically in Figure 2. From the information in Figs. 1 and 2 the variation of structural costs/unit of captured power can be determined as a function of duck stern diameter. This is shown in Figure 3.

It is possible that a minimum unit cost of captured power would be indicated at some duck stern diameter B which is smaller than the value of duck stern diameter A which is required to obtain the high value of exploitation of the resource.

To generalize the argument to other devices only requires that duck stern diameter be replaced by the characteristic dimension (or dimensions) of that particular device - column width for OWCS, cylinder diameter for Bristol Cylinders and so on.

2.2 Power Delivered and the Rating of the Machinery and Transmission Equipment.

For chosen values of the characteristic device dimensions and for devices operating in known sea states the RPT productivity model determines the overall power chain efficiency. This is a ratio of the total power delivered to Perth over the whole year divided by the annual captured power of the device (P above). The power chain efficiency is determined as a function of generator rating; the purpose of the exercise being to optimize the generator rating. The rating of all of the other elements in the power chain follows from the generator rating. A typical curve of power chain efficiency versus generator rating is shown in Fig. 4. The detailed form of the curve depends upon the characteristic performance curves of the machinery and transmission components, the particular ratings chosen for the components in the power chain and also on the captured power of the device and the sea state.

In the course of a design study where the decision has already been made to go for the maximum resource exploitation the large structures which this entails will have proportionally high costs and this fact must dominate the subsequent process of machinery and transmission optimization. This can be seen with reference to Figs. 5 and 6. Fig. 5 shows the costs as a function of generator rating. Fig. 6 shows the total output; this is determined from power chain efficiency shown in Fig. 4 multiplied by the annual captured power of the device. Also shown in Fig. 6 are the unit costs (schematic) of the devices. A generator rating of D gives maximum output from the system and because the total costs in this case are insensitive to the variation in machinery rating the minimum unit costs are obtained by increasing machinery rating to close to the level where output is a maximum i.e. to level C. However, in the course of a design study, where a minimum unit cost criterion is used from the outset, different results may be obtained. Let us suppose that in this case the minimum unit cost of captured power criterion leads to the choice of a structure which is of a much smaller size and hence lower in costs than the case above. Now the process of optimization of the generator and hence power chain rating could be as shown in Figs. 7 and 8. These are analogous to Figs. 5 and 6 except that the total costs are no longer dominated by structural costs and are consequently significantly dependent on the machinery costs and hence the ratings. In this case unit costs can be reduced by lowering the rating of the generator. This of course reduces the output but the cost reduction could more than offset this and result in a significant reduction in unit costs. Now the optimum generator rating, resulting in minimum unit costs is significantly lower than which corresponds to maximum output.

2.3 Distance from Shore

The distance from shore at which the devices are sited affects water depth, sea state and wave alignment at the location. In order to maximise the resource exploitation device teams have tended to choose locations with high power densities which are well offshore.

Moving inshore would have the effect of reducing power density because of energy losses at the seabed and possibly also because of shadowing by headlands. However, these would be compensated to some extent by improved wave alignment and hence improved directionality. There would also be reductions in transmission and mooring costs and lower costs for the smaller structures appropriate to the modified sea state. It may be that these effects would result in a reduction in the unit costs of delivered power.

2.4 Conclusions

It may be that some as yet unidentified, combination of location device size and machinery rating will yeild minimum unit costs of wave generated electricity. These combinations may be close to the reference designs of the current devices in the programme or they may be significantly different, but as yet this is not known because the optimization procedure outlined above has not been systematically applied by device teams.

3. Outline of a Method for the Optimization of Unit Costs

An interactive study of system productivity and of system costs is required as a function of location, device size and rating.

This would need to be done in a step wise fashion in the following stages.

3.1 Stage 1 System Productivity

This would be analysed using the RPT productivity model, for particular locations i.e. distances offshore.

i) Determine the values of

P_{seaij} for the location, then use these to determine the total power available $P_{sea} = \sum_i \sum_j P_{seaij}$

ii) Determine the annual power captured by the device P as a function of the characteristic device dimension(s). This device P as a function of the characteristic device dimension(s). This requires tank test derived values of sea efficiencies η_{ij}

iii) For a range of values of characteristic device dimension determine the power chain efficiency as a function of generator rating R.

iv) Finally from these relationships it will be possible to determine the power delivered to Perth as a function of characteristic device dimension and generator rating.

Families of curves of the type shown schematically in Fig. 9 could be generated.

The feasibility of these studies depends upon the availability of the necessary data from tank tests for all devices over the complete range of characteristic dimensions.

Changing the offshore location will result in a change in wave climate and to take this into account would require that all steps i) - iv) be re-run with new sea state data. However, for this to be possible requires detailed information on the way wave climates vary with distance from shore. Information of this type would be time consuming and hence expensive to collect.

It may be possible to use the more limited information which is available to construct formulae which can be used to transform the curves illustrated in Fig. 9 (which can be determined for well known wave climates) in a way which will make them represent other locations with less well known wave climates.

The end result of this phase would be a model of power delivered to the grid as a function of characteristic device dimension, rating and location of devices.

3.2 Stage 2 Cost and Energy Input Estimation

The purpose of this phase would be to generate a model of system costs and energy inputs as a function of characteristic device dimension, rating and location.

This would be done as follows:

i) Structures - estimate structural costs as a function of characteristic device dimensions

ii) Machinery and transmission - estimate costs as a function of rating and distance to shore.

iii) Moorings or bed preparation - estimate costs as a function of characteristic device size and water depth

iv) Other costs - investigate their dependence on the main parameters of the study.

The area occupied by the combination of all the possible systems in all available locations is bounded by an **envelope** curve. The most attractive combinations of system parameters and locations are those which lie on the envelope **curve.** Also the form of the envelope curve shows clearly the nature of the 'trade off' between low unit costs (or net energy requirements) and resource utilization. Thus, referring to fig. 11 systems in the region of A have the minimum possible unit costs but make poor use of the resource. Moving away from the minimum unit costs to the right and staying on the envelope curve, for instance to B, unit costs increase but better use is made of the available resource. The particular choice of device parameters and locations on the envelope curve depends upon the relative importance of minimum unit costs and of resource exploitation in the context of the particular development programme being considered. In the current U.K. wave energy programme the emphasis on delivered resource must lead device teams to solutions in the region of B in Fig. 11 rather than in the region of A.

It would seem to be important to investigate the complete range of wave energy systems which are possible by diagrams of the type shown in Fig. 11 in all cases to indicate clearly the range of possible minimum unit costs as well as the possible levels of resource exploitation in each case.

Also if a decision is made to build a wave energy prototype it may be more rational to develop a minimum unit cost prototype rather than a maximum resource exploitation prototype. The former could demonstrate the cost effective potential of wave energy, albeit at low resource levels while the latter while demonstrating technical feasibility may reinforce impressions of high costs.

3.3 Stage 3 Determination of Unit Costs and Net Energy Requirements

The combination of the productivity curves determined in stage 1 with the costs and the energy inputs determined in Stage 2 will yeild unit costs of delivered power as a function of characteristic device dimension, rating and location and net energy requirements parameterised in the same way.

3.4 Stage 4 Fraction of Available Resource Delivered

Because the emphasis of this approach is upon the relationship between the unit costs of power which a device deliveres and the fraction of the resource which the device exploits it is useful to determine this fraction for all devices. It can be calculated by dividing:

Power delivered to grid (per device or per unit of frontage) by total Power available: P_{sea} (per device or per unit of frontage)

4. Presentation of Results

For each type of device it will be possible to present a series of curves of unit costs similar to that shown schem atically in Fig. 10. Separate sets of curves representing different device locations would show the sensitivity to siting and from curves of this type it would be possible to identify minimum cost combinations of device characteristics and locations in each case.

Because of the device specific nature of the characteristic device dimension these curves cannot be used to compare directly difference types of device. Nor do the curves give directly information about the effectiveness of the difference devices in exploiting the resource availble. Plotting unit costs against the fraction of the available resource delivered produces characteristic diagrams for each device which can be directly compared and which show their effectiveness in exploiting the resource. Fig. 11 is a schematic diagram of this type.

References

1. Energy Paper No. 42 "Wave Energy" HMSO, 1979, p.17.

2. Rendel, Palmer and Tritton, U.K. Wave Energy Programme Consultants Second Report, August 1978.

3. Rendel, Palmer and Tritton, U.K. Wave Energy Programme Consultants Iterim Report, NEL Oscillating Water Column Device (Bottom Standing Device) November 1979.

4. Harrison, R., Genkins, J., Roberts, F., Note on the Energy Analysis of Wavepower Systems" presented to the Wave Energy Workshop, Heathrow Hotel, November 1978.

5. Putnam, P.C., "Power from the Wind" Von Nostrand, 1948.

Figure 1 Schematic representation of annual power captured versus characteristic device dimension

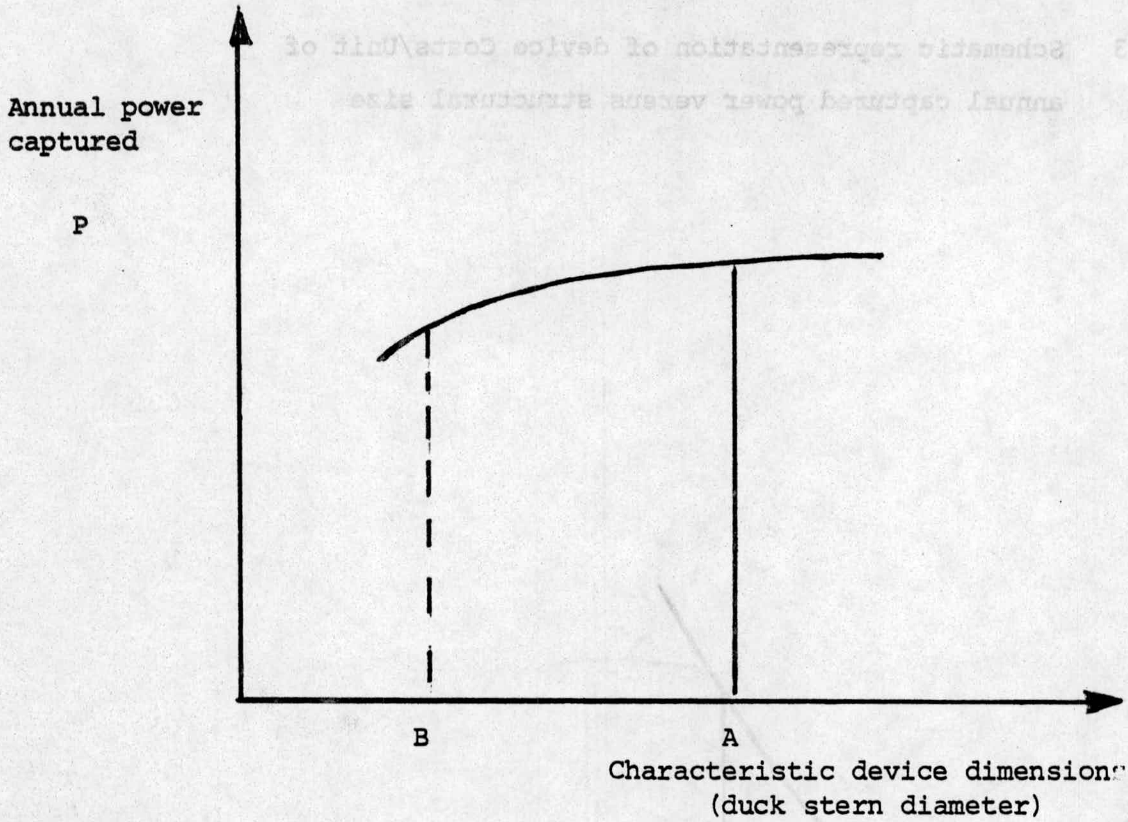


Figure 2 Schematic representation of device costs versus characteristic device size

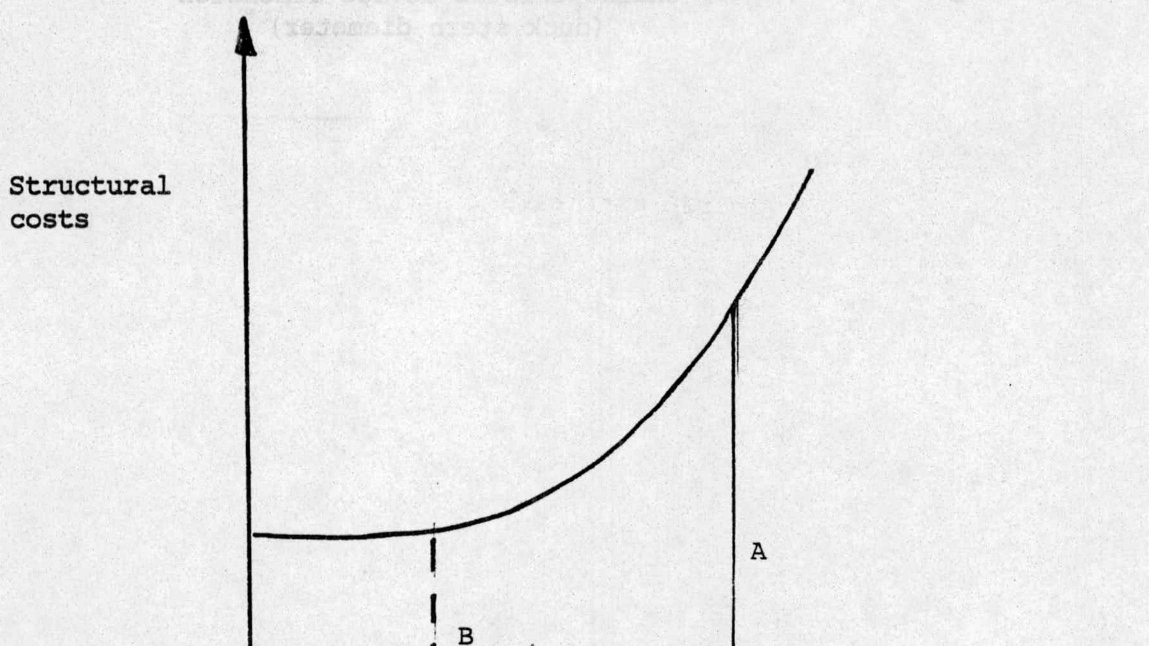


Figure 3   Schematic representation of device Costs/Unit of annual captured power versus structural size

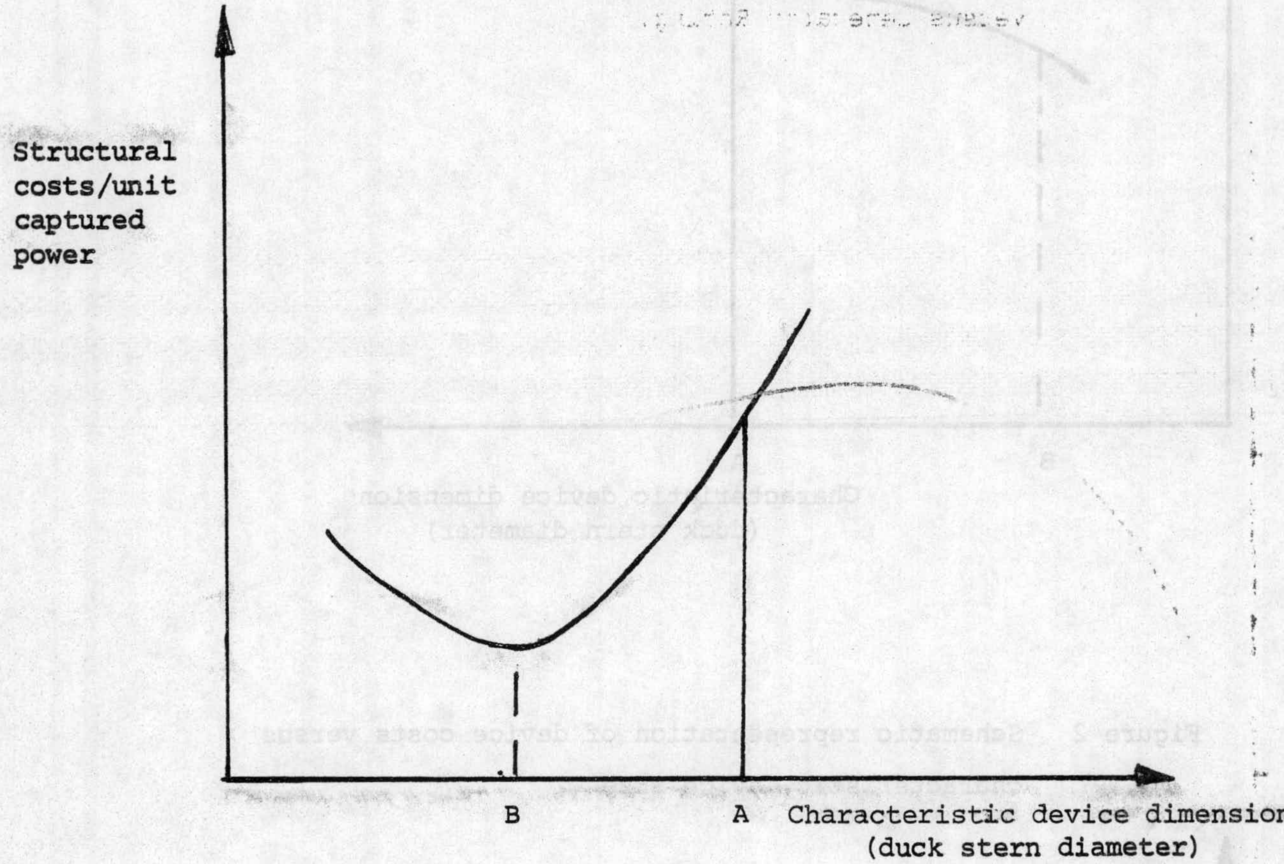


Figure 4   Typical Curve of Power Chain Efficiency Versus Generator Rating.

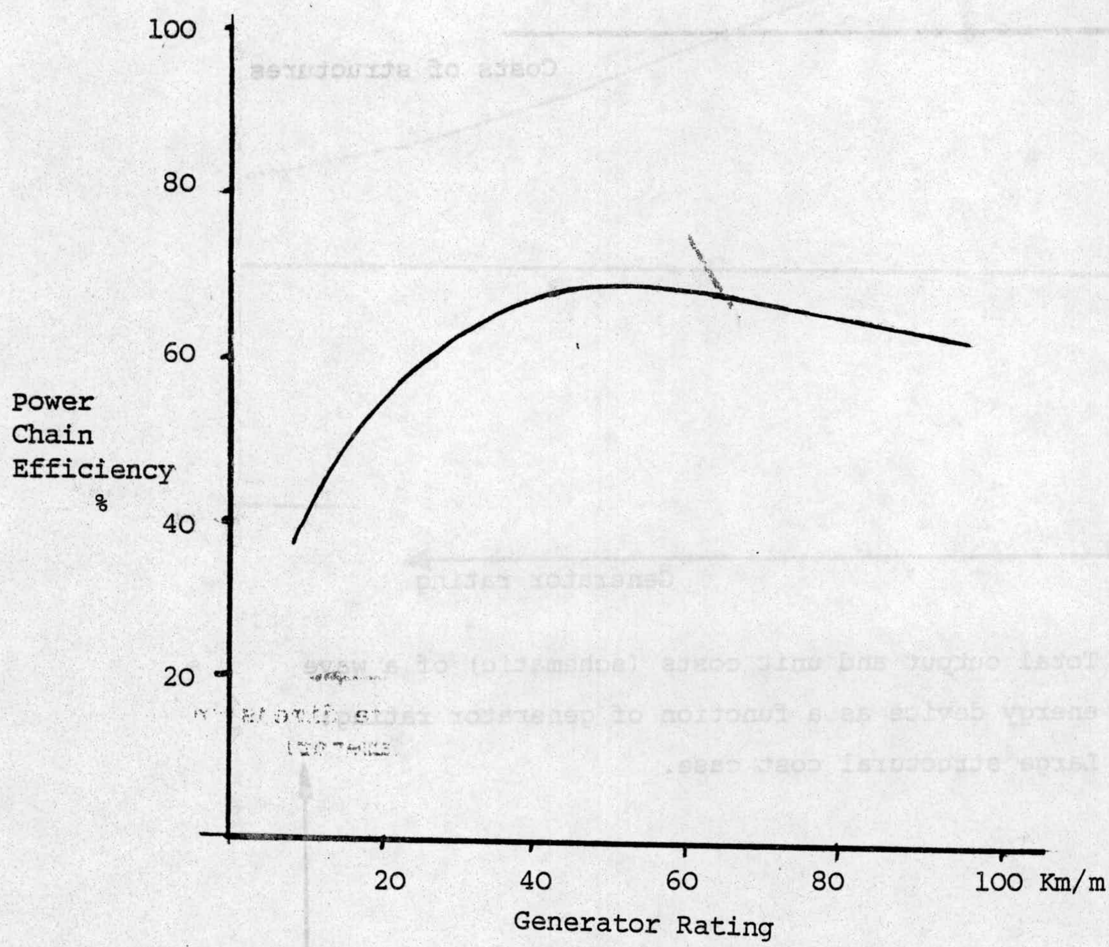


Figure 5 Costs (schematic) of wave energy device as a function of generation rating: large structural costs case.

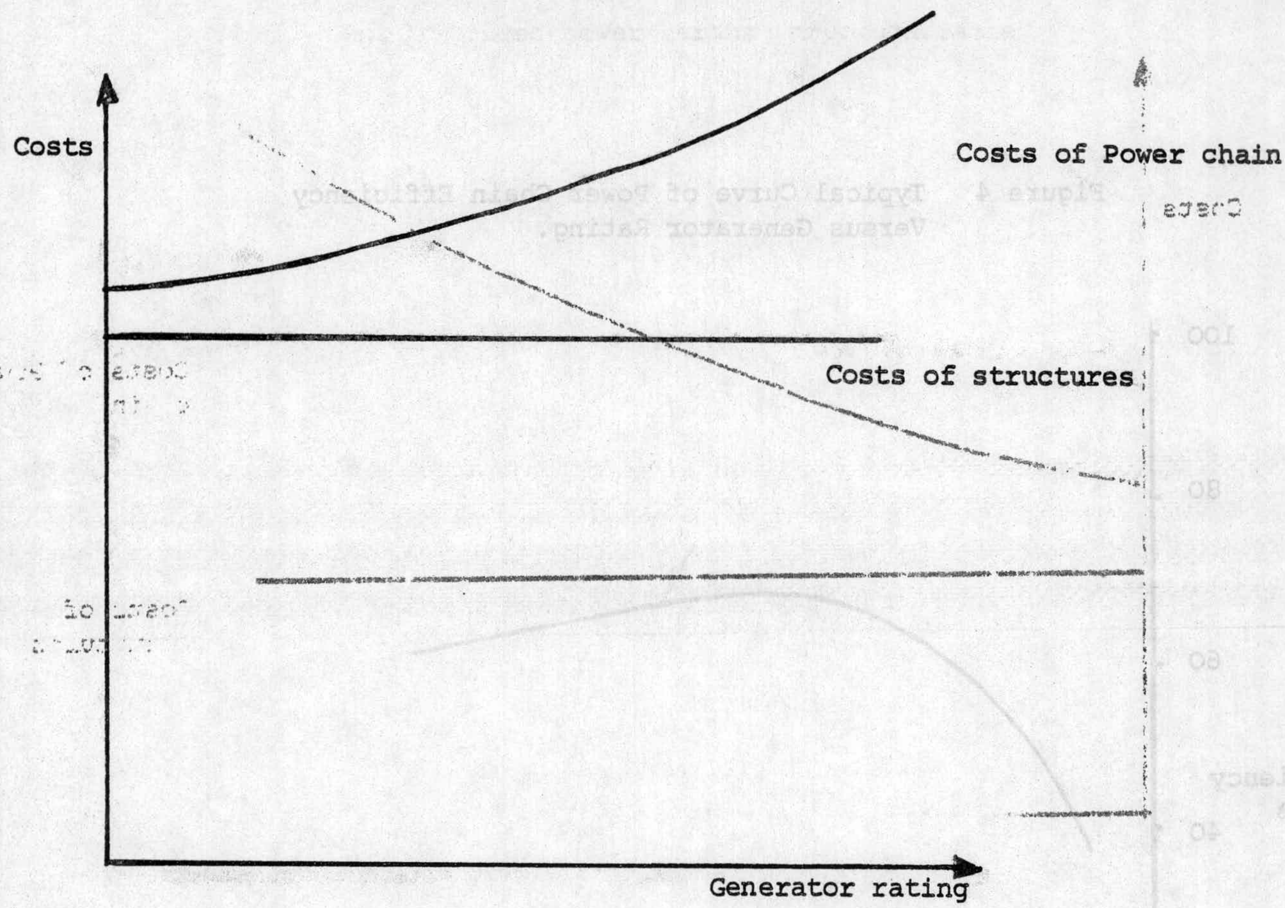


Figure 6 Total output and unit costs (schematic) of a wave energy device as a function of generator rating: Large structural cost case.

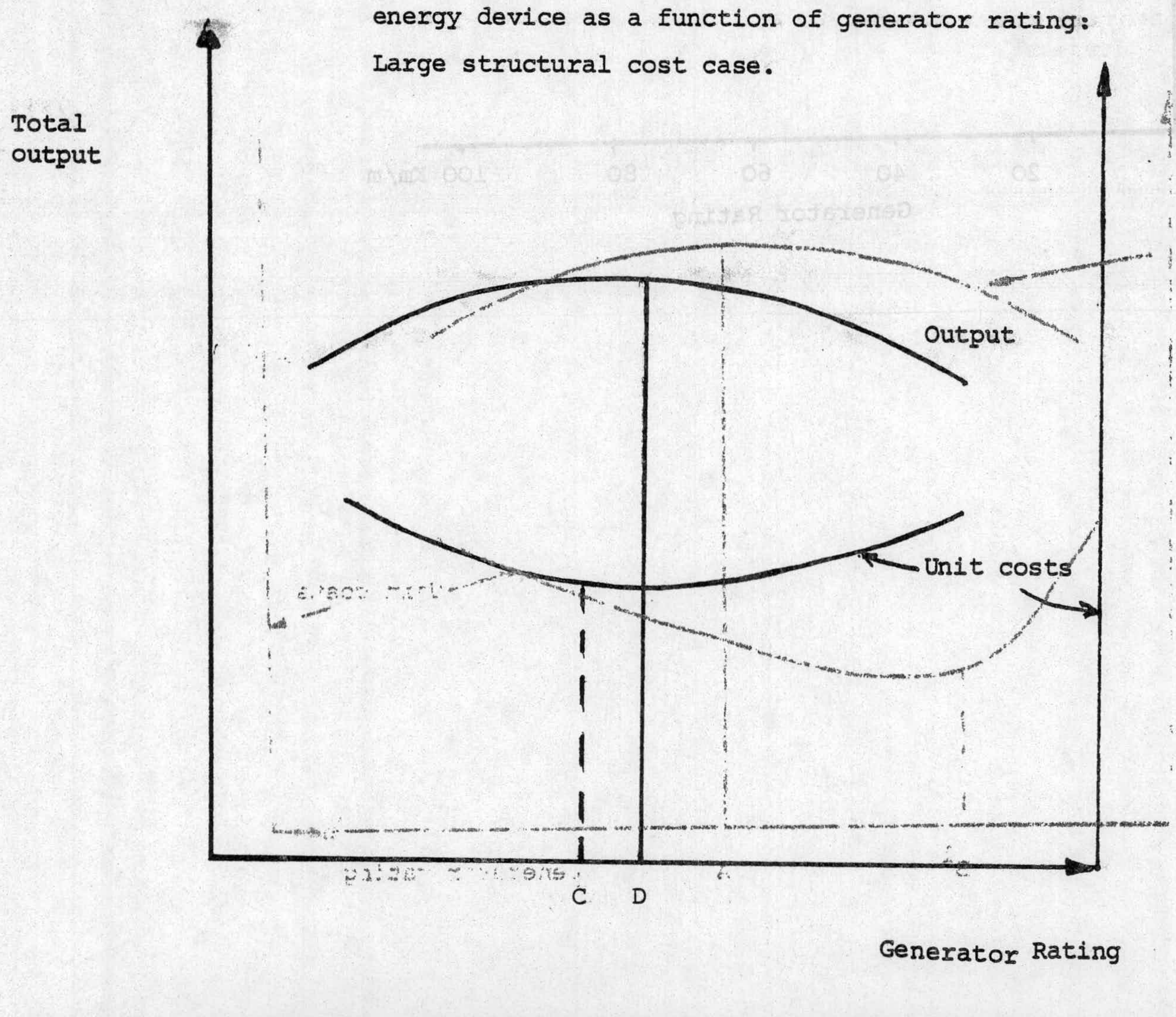


Figure 7 Costs (schematic) of a wave energy device as a function of generator rating: low structural cost case.

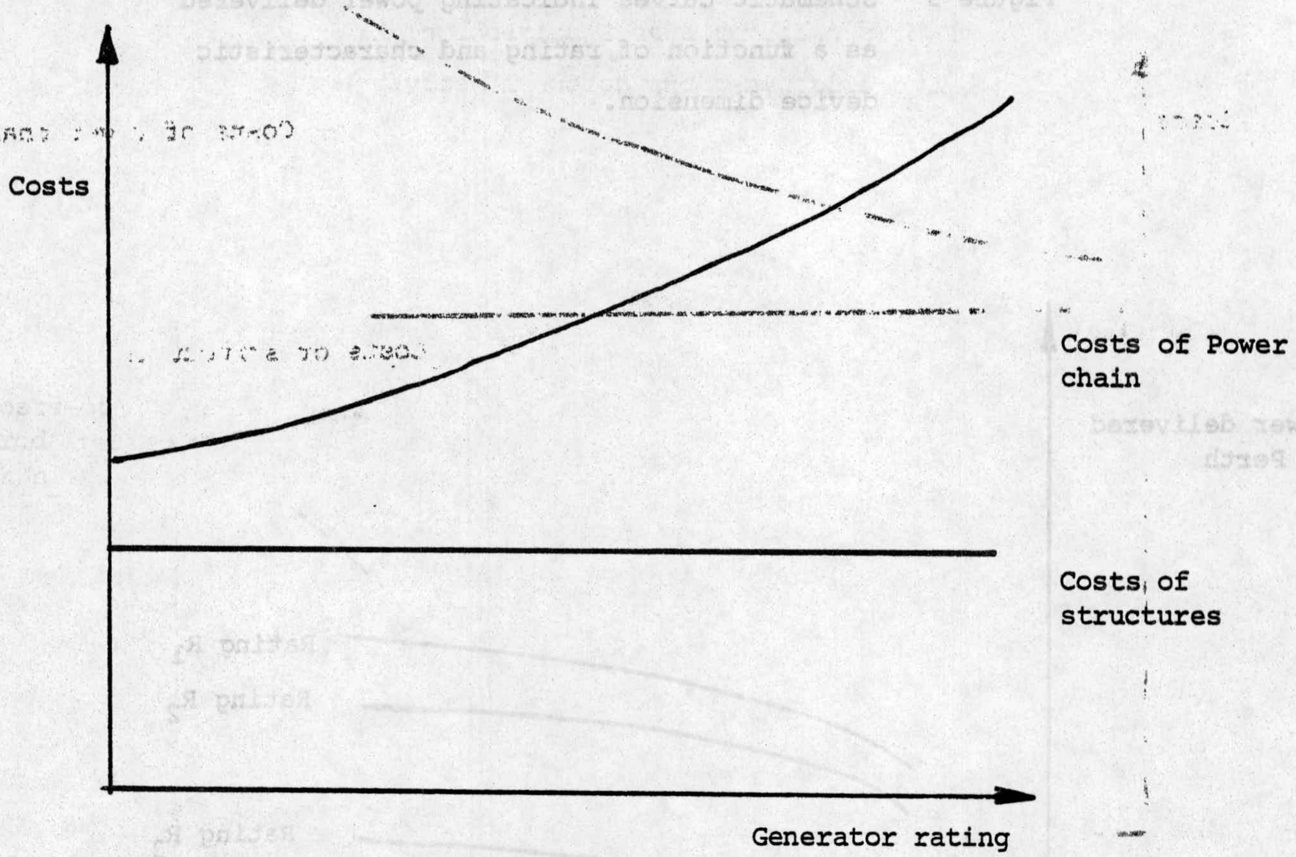


Figure 8 Total output and unit costs (schematic) of a wave energy device as a function of generator rating: low structural cost case

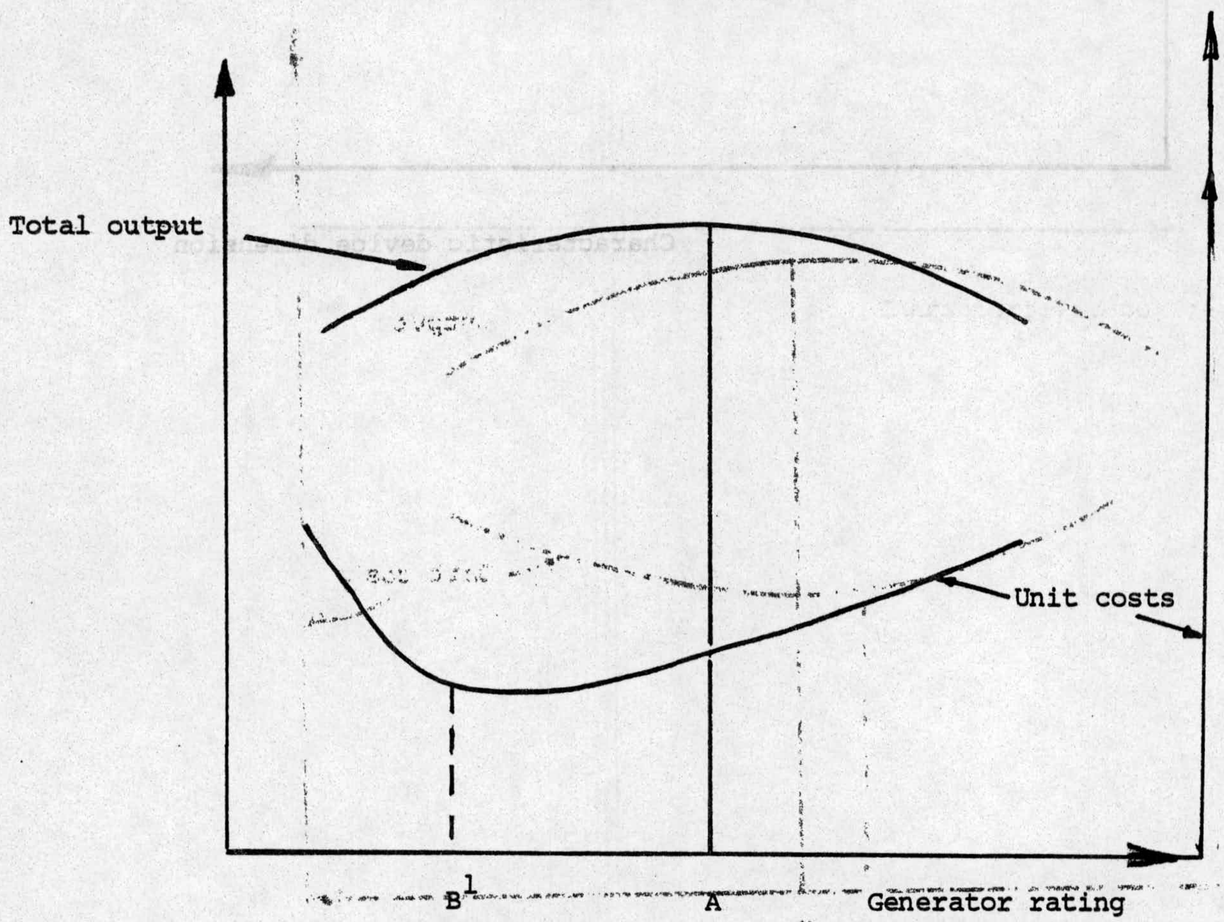


Figure 9 Schematic curves indicating power delivered as a function of rating and characteristic device dimension.

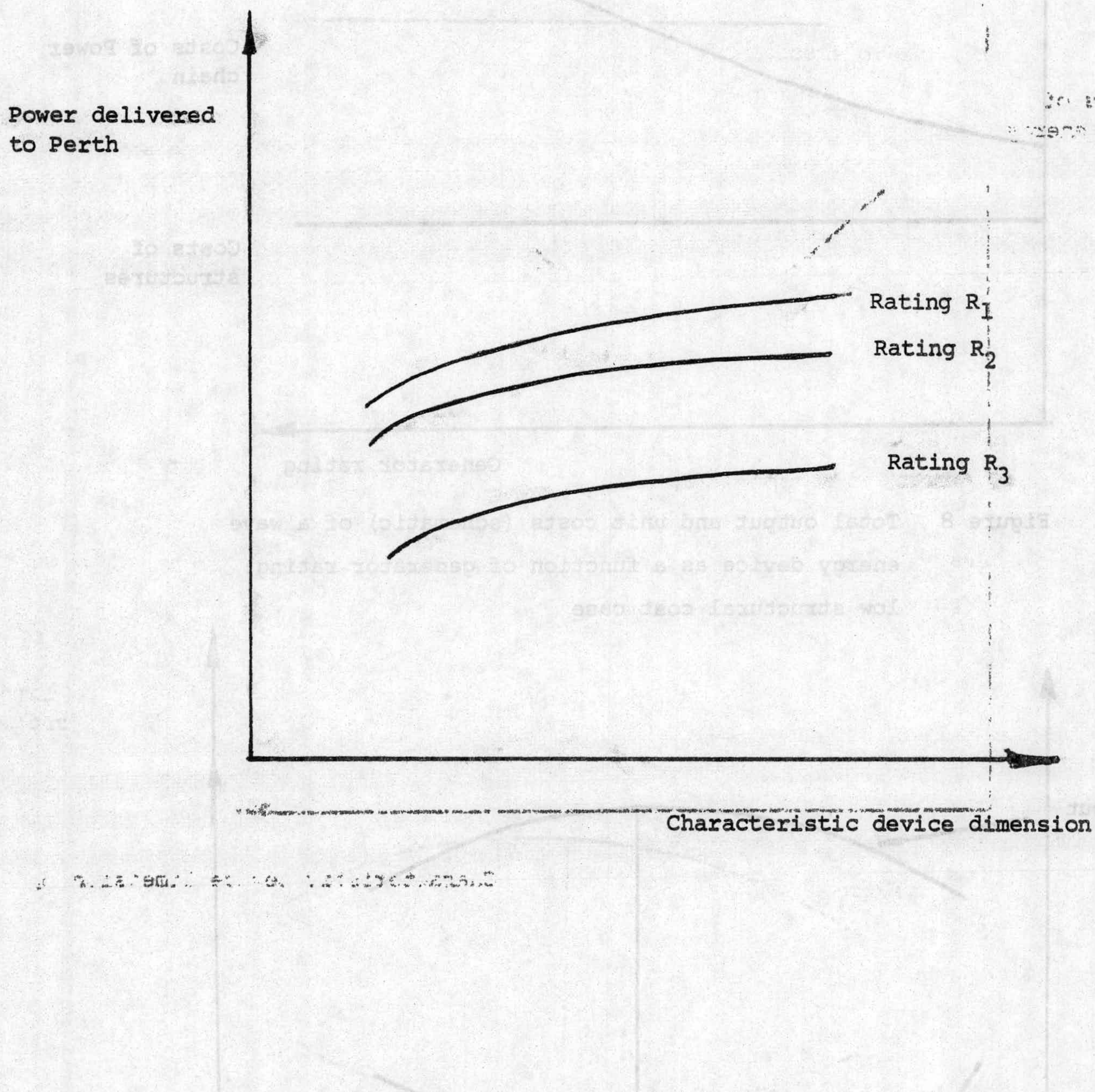


Figure 10 Unit Costs of delivered power for device type X in location Z as a function of Characteric device dimension and generation rating.

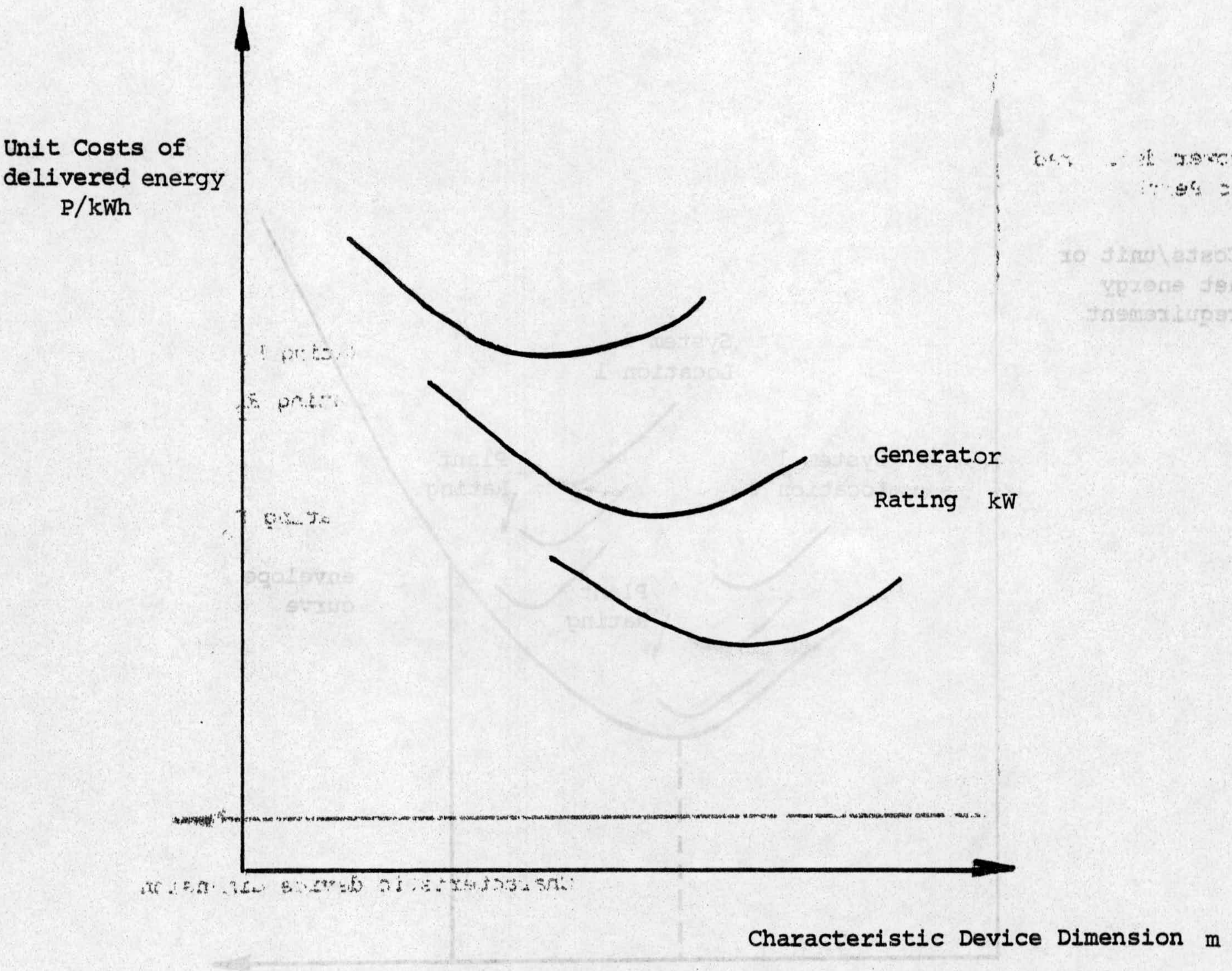


Figure 11 Diagram showing schematically the location of all possible systems in the space unit costs vs fraction of resource utilized.